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Shahab Hasan, Robert Hemm, Scott Houser

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Logistics Management Institute
2000 Corporate Ridge
McLean, VA 22102-7805

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Mary S. Reveley
NASA Glenn Research Center
Aerospace Engineer - Aviation Safety Program
MS60-7
Cleveland, OH 44135

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NASA's Aviation Safety Program (AvSP) seeks to reduce hull loss and fatal accidents. In this task, we developed a method to perform safety benefit analyses of the AvSP technologies. The method comprises two principal analytic components: a reliability model and a simulation model. In the reliability model, we break down the technology into basic components, such as hardware, software, and human agents; define how those components interact; and then determine the failure modes and rates of the components. The results determine how different technologies and systems will perform in normal, degraded, and failed modes of operation. In the simulation, we model an operational scenario and use Monte Carlo methods and specific failures (based on the reliability analysis) to investigate the performance of the technology and identify areas warranting further exploration. The report presents details of the method and preliminary results for the Synthetic Vision and Weather Accident Prevention projects of the AvSP.

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MCLEAN, VIRGINIA 22102-7805

Preliminary Results of an Integrated Safety Analysis of NASA Aviation Safety Program Technologies

NS112S1/MARCH 2002

Executive Summary

Through its Aviation Safety Program (AvSP), the National Aeronautics and Space Administration (NASA) aims to develop and demonstrate technologies that contribute to reducing the aviation fatal accident rate by a factor of five by the year 2007 and by a factor of 10 by the year 2022. Six projects comprise NASA's safety program—synthetic vision system (SVS), weather accident prevention (WxAP), system-wide accident prevention (SWAP), single aircraft accident prevention, aviation system monitoring and modeling, and accident mitigation. LMI is currently supporting a safety benefit analysis of the first three projects. Integrated safety analysis of day-to-day operations and the risks associated with those operations will provide an understanding of the AvSP portfolio not now available. This report is an overview of the method that we have developed for analyzing AvSP and presents preliminary results for SVS and WxAP.

Our integrated safety analysis method comprises two principal components: a reliability model and a simulation model. In the reliability model, we break down the technology into basic components, such as hardware, software, and human agents; define how those components interact; and then determine the failure modes and rates of the components. The results determine how different technologies and systems will perform in normal, degraded, and failed modes of operation. In the simulation, we model an operational scenario and use Monte Carlo methods and specific failures (based on the reliability analysis) to investigate the performance of the technology and identify areas warranting further exploration.

Our basic algorithm for estimating safety is

*P(Accident) = P(Hazard) * P(Accident | Failure and Hazard)*

where

P(Accident) is the probability of an accident,

P(Hazard) is the total probability of a hazardous condition,

P(Accident | Failure and Hazard) is the conditional probability of an accident given a failure when a hazard exists.

The following table shows preliminary results for SVS where safety gain is defined as the baseline-case accident probability divided by the variant-case accident probability. Therefore, a safety gain of 420.0 means that the aircraft is 420 times safer with SV than without SV.

Turn rate (°/s)	Envelope distance (feet)	ATC only $P_{accident}$	SV and ATC $P_{accident}$	Safety gain
1.4	**17,500**	**9.50×10^{-1}**	**8.42×10^{-2}**	**11.29**
1.4	**20,000**	**5.10×10^{-1}**	**2.90×10^{-3}**	**175.8**
3.0	**10,000**	**8.90×10^{-1}**	**6.33×10^{-2}**	**14.05**
3.0	**12,500**	**5.10×10^{-1}**	**2.01×10^{-3}**	**253.2**
5.3	**7,500**	**7.90×10^{-1}**	**3.78×10^{-2}**	**20.91**
5.3	**10,000**	**4.20×10^{-1}**	**1.00×10^{-3}**	**420.0**

Turn rate (°/s)	Envelope distance (feet)	ATC only $P_{accident}$	SV and ATC $P_{accident}$	Safety gain

The turbulence scenario's safety metrics are less obvious than the terrain scenario's safety metrics, so we present several results instead of a single value safety gain. The first table shows encounter probability with and without the WxAP technology and for varying lead-times. The second table shows altitude escape and slowdown probabilities with the WxAP technology for varying lead-times. The third table shows warning times achieved with the WxAP technology for varying lead-times.

Technology	Nominal lead-times (s)						
	30	60	90	120	180	240	300
No WxAP	**0.210**	**0.219**	**0.212**	**0.216**	**0.208**	**0.219**	**0.210**
WxAP	**0.216**	**0.212**	**0.214**	**0.215**	**0.191**	**0.030**	**0.031**

Avoidance/Mitigation Maneuver	Nominal lead-times (s)						
	30	60	90	120	180	240	300
Altitude escape	**0.0**	**0.0**	**0.0**	**0.0**	**0.055**	**0.861**	**0.852**
Full slowdown	**0.0**	**0.0**	**0.169**	**0.875**	**1.0**	**1.0**	**1.0**

Nominal lead-times (s)	30	60	90	120	180	240	300
Warning times (s)	**24.2**	**59.5**	**99.4**	**146.1**	**242.1**	**340.9**	**438.0**

Although these results are preliminary it is clear that, as modeled in our scenarios, the AvSP technologies provide significant safety benefits.

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Contents

Appendix Abbreviations

FIGURES

TABLES

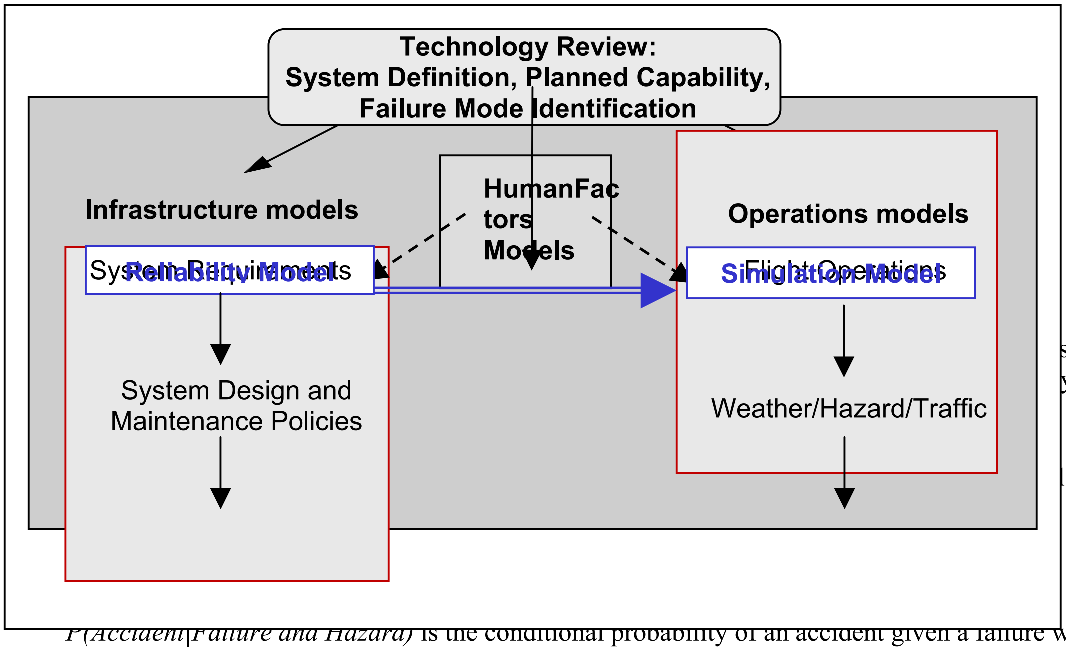
Chapter 1

Overview of Method and Modeling Principles

Overview of Method

The NASA AvSP is investigating technologies to reduce flying accidents and hazardous incidents. Improving safety is a key requirement so air traffic density can continue to grow to meet the continually increasing demand. Integrated safety analysis of day-to-day operations and the risks associated with those operations will provide an understanding of the AvSP portfolio not now available. The goal of our task is to create a flexible analysis tool that accurately assesses the benefits of the AvSP technologies and supports parametric analysis of technology trade-offs. Figure 1-1 depicts the method for an integrated safety analysis.

Figure 0-1. Integrated Safety Analysis



safety

y

. 0-1]

P(Accident|Failure and Hazard) is the conditional probability of an accident given a failure when a hazard exists.

The baseline condition is the case where hazards exist and no new safety technology is available. For this baseline the equation is:

*P(Accident) = P(Hazard) * P(Accident | Hazard* without *technology)* [Eq. 0-2]

The technology case is given by:

*P(Accident) = P(Hazard) * P(Accident | Hazard* with *technology)* [Eq. 0-3]

Not all safety hazards result in actual accidents. For example, we can state a base case for turbulence (where the result is injury rather than accident) as:

$P(Injury)_{Baseline} = P(Turbulence) * P(Injury \mid Turbulence\ and\ Baseline\ Technology)$[Eq. 0-4]

Safety technologies that we add also can fail. For example, technology that predicts and warns about turbulence modifies the probability of an injury during an encounter with turbulence, but also contributes its own probability of failure. The result is that the total probability of injury becomes

$P(Injury)_{Technology} =$

[Eq. 0-5]

*P(Turbulence) * P(Working Technology) * P(Injury | Turbulence and Working Technology)*

*+ P(Turbulence) * P(Failed Technology) * P(Injury | Turbulence and Failed Technology)*

Total failure of the technology would revert to the baseline, but partial failures can result in a reduced detection range, reduced probability of detection, or reduced effectiveness of the alarm, with each failure type having its own conditional probability of injury. As long as the failure types are independent, the results can be summed to determine the total probability of an injury occurring.

In principle, absolute hazard probabilities can be determined from empirical data. The hazard probability depends on the type of accident being analyzed. For example, entering an erroneous waypoint into the flight management system (FMS) computer is one hazard that can lead to controlled flight into terrain (CFIT). The probability of entering erroneous data should be available from historical flight and simulator data. Because entering erroneous data into the FMS computer at altitudes above obstacles never results in CFIT, we should weight the probability of erroneous entries by the fraction of waypoint entries made when aircraft are below the altitude of surrounding terrain. Similarly, for turbulence hazard, the probability of encountering turbulence, or an area of turbulent conditions, should be determinable from historical flight reports.

The hazard probability term in our equation can represent relative probabilities. If a technology not only reduces the conditional probability of an accident for a given hazard, but also reduces the probability of being exposed to the hazard, the benefit of the latter can be applied to the hazard term. For example, strategic weather information should reduce the probability of being on a flight path that intersects a thunderstorm cell, while tactical information and sensors reduce the probability of penetrating the cell if it is on the flight path.

We can estimate the probabilities of degraded and failed technology using Markov failure analyses. To use the Markov failure analyses, we must define the technologies' hardware, component failure rates, and the degraded functionality (such as reduced detection range).

We can estimate the conditional accident probabilities using Monte Carlo simulations. In the simulations, both equipment and human response can be represented by

- detection probability and time,
- decision time and correct decision probability, and
- action time.

These values are functions of technology and scenario parameters. The probabilities and times can be improved by technology, training, and procedures and they can be worsened by hardware failures, workload, and surprise. Simulation values for the times and probabilities are inputs and must come from technology experiments, research of human factors, and subject-matter experts.

Our method enables analyzing the benefits (reduction of incidents, accidents, and encounters) of specific technologies applied in specific scenarios. Our method cannot predict overall national airspace system (NAS)-wide accident rates and accordingly, we cannot validate it by using historic accident rates. Also, we do not intend the method to be used to recreate actual accidents.

Overview Of Modeling Principles

Building a simulation that can model the spectrum of current and future aviation safety projects without additional coding is not feasible. Running a new scenario may require modeling instruments and decision-making processes that no one considered when building the original simulation. To accommodate new scenarios, the programmer must either overgeneralize the simulation, or provide a sophisticated interface that enables users to build their own simulation components and algorithms. Overgeneralizing may eliminate critical details in a scenario. Providing a sophisticated interface amounts to trading programming for scripting. Building a detailed script can be just as complicated as, or more complicated than, programming, and is usually less flexible.

Therefore, because new scenarios inevitably require new programming, we must focus on concepts that apply to several scenarios. The remainder of this chapter discusses three aspects of aviation safety modeling and the concepts that make them applicable to a wide range of safety scenarios:

- Collision and encounter modeling
- Instrumentation modeling
- Human-factors modeling.

By building software that takes advantage of the common characteristics of these three modeling aspects, the time and additional programming required to implement a new scenario can be reduced.

➤ Collision and Encounter Modeling

Many tactical safety scenarios model one object colliding with or enveloping another object. For example, terrain avoidance prevents an aircraft from colliding with terrain. Traffic avoidance prevents two aircraft from colliding with each other. Weather accident prevention prevents a weather cell from "colliding with" an aircraft. The consequences of a collision between two objects may differ drastically. However, the modeling concepts behind these collisions remain similar. We can, therefore, use common algorithms to model them.

Estimating Time to Collision

Often, estimating when a point (i.e., an aircraft) and a larger object (i.e., a weather cell) will collide, or if they will collide at all, is necessary. With this estimate, a pilot may avoid the object in his path. Mathematically, a collision occurs when a non-null intersection exists between the two objects. The algorithm that estimates the collision time calculates the intersection of a point and a block moving in time. For simplicity, assume a Point A with a velocity

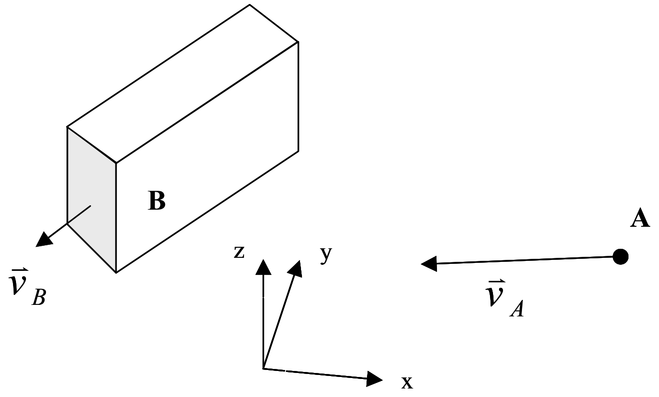
$$\vec{v}_A = v_{A_x}\hat{i} + v_{A_y}\hat{j} + v_{A_z}\hat{k} \qquad \text{[Eq. 0-6]}$$

and a position

$$\vec{p}_A = x_A\hat{i} + y_A\hat{j} + z_A\hat{k} \qquad \text{[Eq. 0-7]}$$

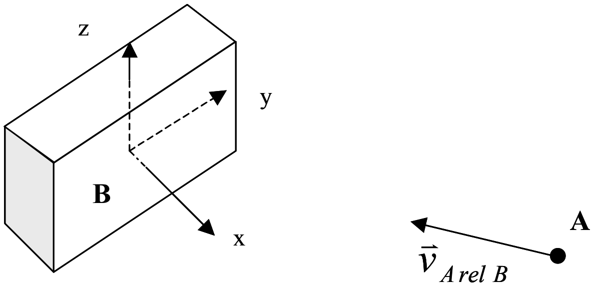
represents an aircraft. Assume that A is on a potential collision course with a terrain object or weather cell, B. Object B is a block with dimensions (S_x, S_y, S_z), where S is defined in the block's coordinate frame. When, if ever, will A collide with B?

Figure 0-2. Point and Object on Collision Course: Global Coordinate Frame



To calculate the probability and time of a collision, using B’s frame of reference is easiest. That is, the coordinate frame in which the origin coincides with B’s centroid, and each of B’s edges are parallel to one of the three coordinate axes.

Figure 0-3. Point and Object on Collision Course: Object’s Coordinate Frame



In B’s coordinate frame, we can define B as a set of three one-dimensional boundaries:

$$-\frac{S_x}{2} \le x \le \frac{S_x}{2}$$
$$-\frac{S_y}{2} \le y \le \frac{S_y}{2} \qquad \text{[Eq. 0-8]}$$
$$-\frac{S_z}{2} \le z \le \frac{S_z}{2}$$

To convert from the global frame of reference to B’s frame of reference, we must find the transformation matrix that relates the global and object-centered frames, and use it to transform both A’s and B’s vertices. This is a straightforward process. Because B’s reference frame moves with it, we must compute the velocity of A relative to B:

$$\vec{v}_{A\,rel\,B} = (v_{A_x} - v_{B_x})\hat{i} + (v_{A_y} - v_{B_y})\hat{j} + (v_{A_z} - v_{B_x})\hat{k} \qquad \text{[Eq. 0-9]}$$

Of course, $\vec{v}_{B\,rel\,B}$ is zero in its own coordinate frame. For the remainder of this discussion, the only velocity we refer to is $\vec{v}_{A\,rel\,B}$, and the only position we refer to is $\vec{p}_{A\,rel\,B}$. Therefore, we will drop the subscript in the remaining equations.

Over time, the position of A with respect to B is

$$\vec{p} = (x_o - v_x t)\hat{i} + (y_o - v_y t)\hat{j} + (z_o - v_z t)\hat{k} \qquad \text{[Eq. 0-10]}$$

where

(x_o, y_o, z_o) define the location of A at $t = 0$

To estimate the time when A first enters the interior of B, we must compute the distance between A and the centroid of B (the origin):

$$d^2 = (x_o - v_x t)^2 + (y_o - v_y t)^2 + (z_o - v_z t)^2 \qquad \text{[Eq. 0-11]}$$

To determine the time at which A intersects B, we must combine Equation 1-11 with Equation 1-8:

$$d_x^{\ 2} = \frac{S_x^{\ 2}}{4} \le (x_o - v_x t_x)^2$$
$$d_y^{\ 2} = \frac{S_y^{\ 2}}{4} \le (y_o - v_y t_y)^2 \qquad \text{[Eq. 0-12]}$$
$$d_z^{\ 2} = \frac{S_z^{\ 2}}{4} \le (z_o - v_z t_z)^2$$

We produce the following relationships by isolating *t* in these inequalities:

$$t_{x_{in}} = \frac{-\frac{S_x}{2} - x_o}{v_x} < t_x < \frac{\frac{S_x}{2} - x_o}{v_x} = t_{x_{out}}$$
$$t_{y_{in}} = \frac{-\frac{S_y}{2} - y_o}{v_y} < t_y < \frac{\frac{S_y}{2} - y_o}{v_y} = t_{y_{out}} \qquad \text{[Eq. 0-13]}$$
$$t_{z_{in}} = \frac{-\frac{S_z}{2} - z_o}{v_z} < t_z < \frac{\frac{S_z}{2} - z_o}{v_z} = t_{z_{out}}$$
$$v_x, v_y, v_z \ne 0$$

If a velocity component is negative, then its corresponding inequality is reversed. Physically, these inequalities describe three time intervals in which A passed through a corresponding boundary of B. If a time is negative, then A passed through that particular boundary in the past. The minimum time for each interval, t_{in}, is the time that A enters the boundary; the maximum time for each interval is the time that A leaves the boundary. Point A must be inside all three boundaries at once to be inside B. The time A spends inside B is, therefore, the intersection of all three time intervals. The intersection produces the following interval:

$$\max(t_{i_{in}}) < t \ < \min(t_{i_{out}}) \qquad \text{[Eq. 0-14]}$$

where

$$i \in (x, y, z)$$

If the maximum entry time is greater than the minimum exit time, then the intersection does not exist. This means that A never crosses inside of B. Further, if the minimum exit time is positive, that means that A has been inside B in the past, but will not enter B again. For example, consider the following solution set:

$$5 \le t_x \le 10$$
$$8 \le t_y \le 12 \qquad \text{[Eq. 0-15]}$$
$$7 \le t_z \le 13$$

The intersection of the intervals in this solution set yields the total time that A is inside B:

$$8 \le t = t_x \cap t_y \cap t_z \le 10 \qquad \text{[Eq. 0-16]}$$

In other words, A first enters B at time *t* = 8, and exits B at time *t* = 10.
All velocity components must be non-zero. When one or more of the velocity components is equal to zero, then the intersection reduces to the maximum entry time and the minimum exit time for each of the

components with non-zero velocities. A further check is required to determine if the position of each component with a zero velocity falls inside or outside of B. If, for example, $x_o = 4$ and $v_x = 0$, then A will never collide with B if B's boundary on the positive x axis is less than 4. If this boundary is greater than 4, then the intersection time interval is

$$\max(t_{y_{in}}, t_{z_{in}}) < t \ < \min(t_{y_{out}}, t_{z_{out}}) \qquad \text{[Eq. 0-17]}$$

The algorithm described above enables us to simulate a pilot's estimate for arriving at a trouble spot. It also enables us to simulate a pilot's estimate of how large a trouble spot is in terms of time that the plane is exposed to a hazard. The ability to generate these estimates efficiently enables us to model a pilot's actions depending on the size and proximity of a hazard. For example, pilots fly through or over small patches of dry turbulence frequently. However, usually pilots go around large convective weather cells.

The geometry described above is relatively simple, but we can use it to build more complex models. For example, it is possible to define a large obstruction, such as a mountain, as a set of block elements. To determine the projected penetration time for an aircraft flying towards the obstruction, we must determine the projected penetration time for each of the elements. The larger the set of elements, the more accurate the model will be. However, larger models are more difficult to build and can require large amounts of computing time. The user must determine the appropriate level of complexity for his particular simulation scenario.

DETECTING AN ACTUAL COLLISION

During simulation, at any given time step, we can detect an actual collision between an aircraft and another object. If we continue to represent the aircraft as a single point and a larger object as a block (or aggregate of blocks), then computing the distance between them is simple. The block data structure that we use to build elements in terrain objects and weather cells has a normal vector *n* for each of its six faces. With this vector, we can represent the plane that contains a face as a *half space*:

$$0 = n_x x + n_y y + n_z z - (n_x x_0 + n_y y_0 + n_z z_0) \qquad \text{[Eq. 0-18]}$$

where

x_0, y_0, and z_0 = the coordinates of one of the face's vertices.

The half space has a useful property: We can determine the distance *d* from the half space to any point by plugging that point into the half-space equation. If we use point A and block B from the preceding section, the distance between A and the half space that holds a face in B is

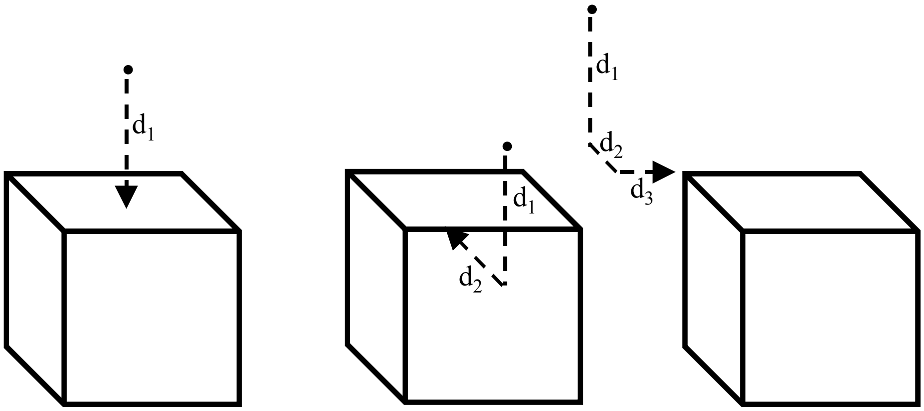
$$d = n_x x_A + n_y y_A + n_z z_A - (n_x x_0 + n_y y_0 + n_z z_0) \qquad \text{[Eq. 0-19]}$$

Furthermore, *d* is directional: If *d* is negative, we know that it is on the inside of the half space; if *d* is positive, we know that it is on the outside of the half space. We can use the directional property of *d* to determine the distance from point A to object B as follows:

- Plug A's coordinates into the half space equation of each of B's six faces. If A is inside B (a collision has occurred) all six of the d_is will be less than or equal to zero. In that case, the model defines the distance between the solid and the point as zero.

- If the point lies outside the solid, it will lie outside one to three of the solid's faces. Figure 0-4 shows these three possibilities.

Figure 0-4. Distances from a Point to a Rectangular Solid



$D = d_1$ $D^2 = d_1^2 + d_2^2$ $D^2 = d_1^2 + d_2^2 + d_3^2$

- Square all non-zero d_is. Sum them and take the square root of the sum to get the distance from the point A to the block B.

This algorithm generalizes collisions between a point and an aggregate object of several block elements. Its simplicity means that it will detect collisions very quickly, even for a complex object. However, a tradeoff between computational speed and detail remains, and the user must carefully consider the amount of detail required for modeling a specific object.

For the majority of cases, collisions between aircraft can be modeled with an even simpler algorithm. Each aircraft is represented as a sphere: each sphere's center is the location of an aircraft, and its radius is a no-fly distance. If two spheres intersect (their centers become closer than the combined length of their radii) then a collision has occurred. This algorithm has been used widely in other aviation safety simulations. By using these two algorithms (point–block and sphere–sphere), we can efficiently detect collisions between almost any pair of objects that are useful to model.

➤ Instrumentation Modeling

All safety scenarios must take into consideration the effects of instrumentation. Hazards that cannot be detected and measured are hazards that a flight crew cannot actively avoid. Modeling all of the instrumentation required in every safety scenario is not possible; too many types of instruments and too many parameters must be considered. Also, too many physical differences exist between instruments, even those that are used for the same purpose. For example, an altimeter may get its value from atmospheric pressure, by bouncing a radar beacon off the ground, or through information from a Global Positioning System (GPS). Each of these systems uses different physical principles to measure the altitude, and, therefore, have different instrument lags and sources of error. Fortunately, most of these instruments share certain similarities. We can use these similarities to minimize the effort for creating a new instrument.

We classify as instruments all avionics that measure one state parameter of the aircraft. A piece of equipment may measure several parameters. However, each software model of an instrument models a single measurement process. A software model of a measurement process has the following common elements:

- The measured parameter
- One or more other parameters used in the measurement
- An error generator
- An instrument lag

- Indicated and exact values for the parameter
- A maximum effective range.

For example, the measured parameter of an altimeter is the altitude. The altitude, however, may be derived from one or more other parameters. Consider an altimeter that uses the atmospheric pressure to measure altitude. To model the error associated with this instrument, we must understand the sources of error associated with measuring the atmospheric pressure. For example, does the gauge get more or less accurate as the aircraft flies higher, or is it equally accurate at all altitudes?

The error generator uses a specific model to simulate the error in a measurement. For example, if an altimeter has an error that increases linearly with altitude, the error generator would generate a random error value, then multiply that number by the exact altitude to create the indicated altitude. If the error is independent of the altitude, then the error generator would simply add a random error value to the exact altitude to create the indicated altitude. These error generators are relatively simple; more complex generators can be created. For example, an error generator for a radar model can generate errors for a combination of parameters, such as pulse length, azimuth, and range, and combine them to create an indicated value.

An instrument also may lag between the time it registers the measurement and indicates its value. For example, air traffic control radars have a typical sweep time of approximately 5 seconds. Therefore, the information that they provide—primarily the location of aircraft—may be 5 seconds old when the controller observes it. Lag time can be important in a safety scenario. In fact, an instrument's lag time can affect safety more than its accuracy does. Therefore, each instrument must update its indicated value at user-specified intervals. If other simulation objects, such as a pilot or controller, ask for the indicated value several times between updates, the instrument should return the same indicated value each time.

The effective range of an instrument also can affect a safety scenario. When applicable, instrument models should store their maximum range, and return a default value when asked to measure something beyond its range. For example, if the instrument measures the distance to a turbulence cell, it should not show a measurement until an edge of the cell comes within the range of the equipment.

LMI developers have created a software library of base classes for avionics instruments that incorporate the concepts of an error generator, a user-defined interval between measurements, and the maximum range of the instrument. With this library, additional programming still is required to create new instruments for new safety scenarios. However, much of the work required for modeling the instrument and its error exists in the library. The library not only saves programming time, it reduces the likelihood of modeling errors by standardizing the way new instruments are implemented in software.

➤ Human Factors Modeling

Human factors modeling is arguably the most complex aspect of safety simulation modeling. Therefore, our goal in modeling human factors is two-fold:

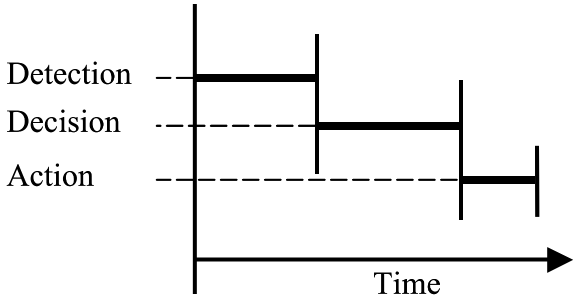
- Make it complex enough to capture the important human factors in a wide range of safety scenarios
- Make it simple enough to avoid excessive implementation time and clear enough that the analyst understands the model.

These goals do not necessarily conflict, but trade-offs exist. If decision making becomes too complex, we believe that modeling that process separately is best. The results then can be fed into the aviation safety simulation where appropriate. When the purpose of a complex human-factors model is to provide the probability of putting an aircraft into a hazardous situation, then a separate model fits nicely with the LMI paradigm of generating a total accident probability. Recall that the purpose of the simulation is to provide the probability of an accident for a specific hazard and/or a failure. The detailed human-factors model can show the probability of a hazard, and the aviation safety simulation can show the conditional probability of an accident. The safety simulation would still need to model human factors, but those human factors would be restricted to what happens *after* the separately modeled human error places the aircraft at risk.

We restrict the simulation's focus as narrowly as possible to avoid the need for complex modeling considerations, such as for load factors, concurrent tasking, and priority-based task scheduling. Our model creates a generic structure for a single human action, and strings together those actions in series and parallel as appropriate. The resulting string of actions is called an action sequence for the scenario. The contents of action sequences change from scenario to scenario. However, their basic structure remains the same, which simplifies the programming required to implement them.

A single human action has as many as three components, each of which occur sequentially: a detection (or recognition), a decision, and an action. Each of these components is a stochastic variable with units of time and is a function of a random number. Figure 0-5 shows how three such components may be added to produce the total time required for a specific action. Each of these values is, in fact, probabilistic and may vary; the figure represents these by showing their expected values.

Figure 0-5. A Single Human Action

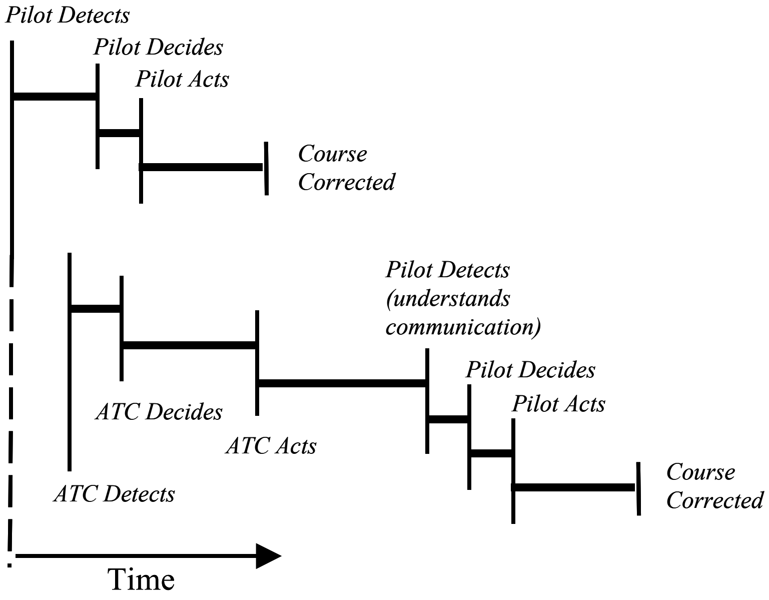


Each of these three components requires a random draw to determine its duration. The times also can be zero: for example, the pilot can decide to turn as a result of recognizing some stimulus; once the decision is made, the amount of time required to initiate the turn may be significantly smaller than the simulation step size. Therefore setting the action time to zero is reasonable. Also, modeling these three separate components in the aggregate by using a single random draw is reasonable.

Acceptable models of tactical human factors can be built by combining a set of actions into a sequence. The sequence itself can have several branches that can run in parallel or series. Naturally, the programmer should keep these sequences as simple as possible. Otherwise, the effort to compute the effects could increase to excessive levels, and the model will be hard to verify. However, even simple models can support multiple human actors who act independently and in concert to correct problems that they see on their own.

An example is an aircraft that has strayed off course. The action sequence that leads to corrective action has two possible routes: the pilot can diagnose the problem using his onboard indications and correct the course, or the air traffic controller (ATC) can discover the problem on his radar and order the pilot to correct the course (see Figure 0-6). If the pilot acts without prompting, only a single action is required: the pilot must correct his course. If the ATC must prompt the pilot to act, then two separate actions are required: the ATC must prompt the pilot, and the pilot must correct his course as prompted.

Figure 0-6. Action Sequence for a Course Correction



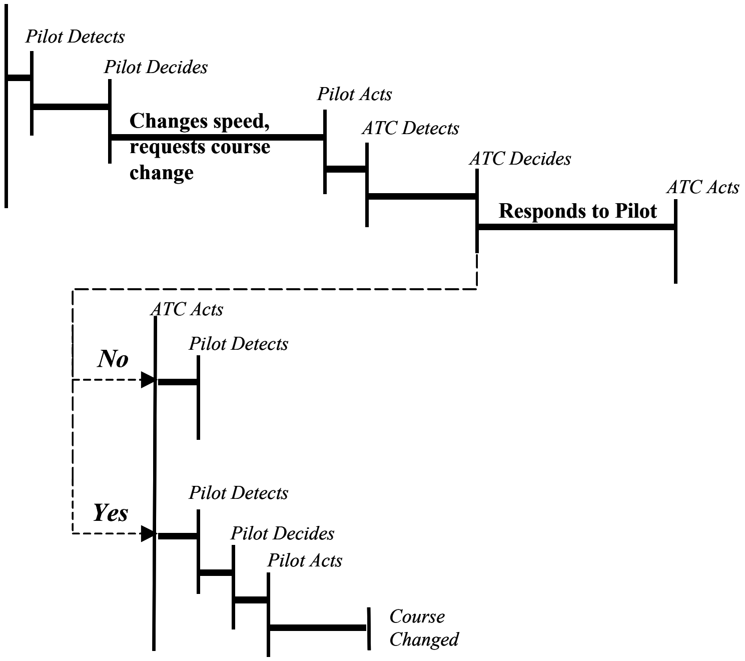
If we interpret the time intervals shown in Figure 0-6 as expected values, clearly, the pilot should usually act without prompting. We have this expectation for several reasons. First, the aircraft's indicators will show the problem before the ATC's radar will. This occurs because the update rate of the ATC's radar is approximately 5 seconds; the aircraft indicators are updated more frequently. Second, the ATC's action, which is communicating with the pilot, takes longer than the pilot's action, which is changing the course. Finally, the ATC's actions only prompt an additional action by the pilot. We expect the pilot's action to take almost the same amount of time as it would if the ATC never prompted him.

The above action sequence implies that the pilot can concurrently talk to the ATC and act to monitor and correct his course. That may not, in fact, be the case. If the simulation user believes making one activity exclusive of the other is important, then he can "turn off" one of the two branches when the other branch gets to a resource-intensive activity, such as communication. In addition, the above sequence does not consider the possibility of an audible alarm or other indication that may occur later than the original indication, but prompt a faster reaction. Including this capability as a third branch in the sequence is straightforward.

The above action sequence does not model decisions with multiple outcomes. For example, a pilot may be able to change his speed without requesting permission, but may need ATC permission to change his course. The ATC may accept or deny a course change request depending on the effect that the course change would have on his traffic sector. For scenarios that include requesting permission, creating an additional random variable that shows the outcome of the ATC's decision, and branching the action sequence to treat each outcome, is simple.

Figure 0-7 shows how such a sequence might work. After the pilot communicates his request for a course change, the ATC takes time to consider it. Regardless of the outcome, he must communicate his decision to the pilot. After the communication occurs, the pilot must understand the ATC's communication. If the ATC says yes, then the pilot must decide how to execute the course change, and then act to change his course. Because the pilot has requested the course change, he may not need to decide anything once the ATC gives his approval. If the ATC rejects the request, the pilot does not need to make further decisions or take further action, and the action sequence ends.

Figure 0-7. Action Sequence with Conditional Branching



As we have shown, our current human-factors model is reasonably flexible for a user who models a tactical safety scenario. The flexibility is sufficient for limited strategic scenarios as well. As it is currently constructed, the model does not consider variable workload of the human actors, and offers only limited modeling of concurrency and incompatibility among tasks. However, the model is a straightforward, logical way to model sequences of human actions, and it enables creating new sequences for new safety scenarios efficiently.

Chapter 2

Our Understanding of AvSP Projects

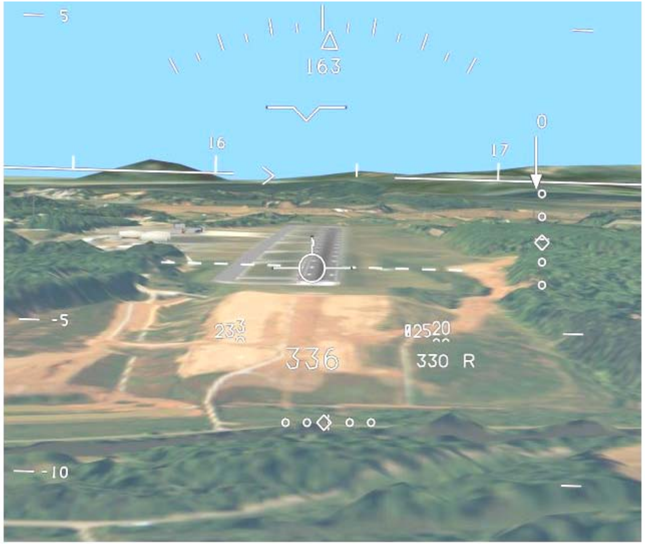
Synthetic Vision

Our understanding of synthetic vision (SV) technology is based on our previous benefit analysis of SV technologies, and descriptions of SV content, characteristics, and expected performance in several sources, including the *Concept of Operations for Commercial and Business Aircraft Synthetic Vision Systems*, and the *Synthetic Vision Systems Project Plan*.

The synthetic vision system (SVS) implies that the pilot will have computer-generated views of the external environment. The SVS presentation is completely artificial. Typically, the presentation is based on a geographical and cultural database supplemented by dynamic traffic information. For terrain, current experimental implementations of SV use GPS data to dynamically link the terrain database to the aircraft's position and attitude. Supplemental sensors may be used to confirm the GPS data or provide additional data (e.g., data about other aircraft, weather, ground equipment). Information about airborne and ground traffic may come from several sources, such as automatic dependent surveillance—broadcast (ADS-B), or a cockpit display of traffic information (CDTI). SVSs can use both head-up and head-down displays. Head-up displays are necessary for older aircraft that do not have panel space for a large head-down display, and may be necessary on all aircraft for the system to be certified. Displays can include an artificial out-of-the-window view (in all directions) or a variety of symbolic and map presentations. Figure 2-1 shows a sample SV display.

The primary purpose of SV is to improve safety by providing visual flight rule- (VFR-) like situation awareness during instrument conditions. SV also should significantly benefit operations, such as VFR-like operations in all instrument flight rule conditions down to Category IIIb. The benefits will occur even at airports that cannot use instrument landing systems because of terrain interference. SV also should enable independent approaches to closely spaced parallel runways, reduced in-trail separations between arriving aircraft, and low-visibility ground operations.

Figure 0-1. SVS Depiction of Approach to Ashville, NC



The Synthetic Vision System Project Plan contains the following objectives:

- Develop and demonstrate affordable, certifiable synthetic vision display concepts that provide enhanced terrain awareness for proactive avoidance of CFIT [Controlled Flight into Terrain] precursors (including retrofit) by presenting intuitive out-the-window terrain and obstacle information suitable for commercial transports, business jets and general aviation (GA) aircraft.

- Develop and demonstrate enabling technology to provide intuitive guidance cues with necessary terrain and obstruction information for precision approach and landing using terrain, obstacle, and airport databases and GPS derived navigation.

- Develop and demonstrate enabling technology to enhance airport surface awareness, including displays of surface routing information, other traffic information, and runway incursion alerts obtained from surface surveillance systems and automated incursion-alerting systems.

- Validate through high fidelity simulation studies that proposed display concepts reduce CFIT, runway incursion (RI), and other visibility-induced fatal accident rates.

- Develop and demonstrate the operational benefits (compelling business case) of synthetic vision systems that will motivate the commercial aviation industry to invest in SVS development, acquisition, and implementation while improving CFIT avoidance.

- Support the implementation of developed technologies through systems engineering, integration and certification planning and demonstrate conformance of technologies with the evolving communication, navigation, and surveillance (CNS) environment and the evolving national airspace system (NAS).

The first three objectives are directly related to developing systems and the remaining three are aimed at validation, industry motivation, and implementation support. Our current analysis enables us to estimate the benefits of SV in avoiding CFIT (Objective 1). Planned analysis also will address RI accidents and airborne traffic avoidance (Objective 3). Our analysis (current and planned) also indirectly covers Objective 2 because our scenarios model approaches and landings. The specific SV scenario is described fully in the following chapter.

Weather Accident Prevention

Our understanding of the Weather Accident Prevention (WxAP) project is based primarily on the *Weather Accident Prevention Project Plan* and the proceedings of the *2nd Annual Aviation Safety Program Weather Accident Prevention Review* held in June 2001.

The WxAP project was created to address the fact that approximately one-third of commercial aviation accidents are at least partially attributed to adverse weather. Although the weather itself cannot be changed, timely and accurate information about weather could reduce accidents caused by weather. The intended products of the research include cockpit weather displays and presentations, hazard avoidance systems, enhanced strategic flight planning tools, turbulence detection and mitigation techniques, and advanced aviation communications.

The Weather Accident Prevention Project Plan includes the following objectives,

- Develop technologies and methods that will provide pilots with sufficiently accurate, timely, and intuitive information during the en-route phase of flight, which, if implemented, will enable a 25–50 percent reduction in aircraft accidents attributable to lack of weather situational awareness.

- Develop communications technologies that will provide a 3-5 fold increase in datalink system capacity, throughput, and connectivity for disseminating strategic weather information between the flight deck and the ground, which, if implemented along with other supporting technologies, will enable a 25–50 percent reduction in aircraft accidents attributable to lack of weather situational awareness.
- Develop turbulence prediction technologies, hazard metric methods, and mitigation procedures to enable a 25–50 percent reduction in turbulence-related injuries.

The first two objectives are aimed at generating and disseminating accurate and timely weather information on the ground and in flight. The last objective is aimed at airborne detection and avoidance of turbulence. Our current analysis enables us to estimate the benefits of WxAP for detecting turbulence and either avoiding it altogether or mitigating its effect if it cannot be avoided (Objective 3). We have not currently modeled the benefits of the information dissemination and communications technologies (Objectives 1 and 2). The specific scenario for WxAP is described fully in the following chapter.

Chapter 3

Modeling Aviation Safety Program Technology with the LMI Safety Model

NASA has tasked LMI to model three AvSP technologies:

- Synthetic vision
- Weather accident prevention
- System-wide accident prevention (SWAP).

Each of these technologies are multipurpose: they may affect several disparate safety scenarios each. Sometimes these technologies may affect a scenario synergistically (for example, SWAP and SV may lower accident probabilities in controlled flight into terrain (CFIT) scenarios more than either might on their own). Each technology also addresses scenarios that are unlike the scenarios that the others address. So far, we have focused on SV and WxAP and this report covers only those two technologies.

For one simulation to practically model each of the technologies meaningfully, we had to focus on the similarities and differences between the scenarios that these technologies affect. For example, CFIT and turbulence avoidance and mitigation are two scenarios with common characteristics. In both, the flight crew wants to detect that they are heading toward a large, undesirable object as soon as possible so that they can minimize the threat of the object. In the case of terrain, the flight crew must avoid that object altogether. In the case of turbulence, going through it usually is acceptable. However, the flight crew will at least want ample warning to prepare those on board for rough going. They also will want to enter the turbulence cell at the ideal penetration speed for that aircraft. In addition, they may want to change altitude, or even turn in extreme cases, to avoid the cell.

The LMI safety simulation constructs both of these scenarios using similar data structures. In the modeling, we stress the concept of making each scenario as simple as possible. We strive to create scenarios only as complex as necessary and sufficient to model the benefits of the technology. Simplicity is critical for several reasons:

- It minimizes customizing the simulation to model a new scenario. This, in turn, minimizes the risk of errors in the code and makes the code easier to troubleshoot.
- It reduces the computation time required to run a reasonable number of scenarios. Excessively detailed scenarios may take a prohibitively long time to run.
- A properly focused scenario increases the conditional probability of simulating an accident, so the simulation can produce meaningful results within a feasible number of runs. This is the most important consideration in aviation safety simulation; it also is the motivation for LMI’s two-step approach to safety modeling.
- It makes the results easier to understand and interpret. Aviation safety is a complex issue; if a scenario is too complex, the analyst may not be able to verify the results, and may not even be able to understand why, or if, the results are valid. Because of the complexity of aviation safety, being able to reproduce results from one analysis in at least one other independent analysis is crucial. By keeping the scenarios clear and simple, such independent analysis is feasible.

When designing the scenarios that we used to evaluate the potential safety impacts of the SV and weather avoidance technologies, we strove for scenarios that we could verify through analytic methods as much as possible. Such verification gives us confidence that our results make sense, and that the simulation algorithms work properly.

Each scenario has a non-AvSP baseline and an AvSP variant. The scenario, therefore, measures the safety benefits of the AvSP technology as a reduction in the probability of an accident from the baseline case, rather than as an absolute probability of an accident. Trying to compute an accurate accident probability is difficult, even for the baseline case, because accident probabilities are dependent on many circumstances, including the following:

- Object geometry—the shape of a terrain obstruction or the shape, velocity, and intensity of a turbulence cell
- Aircraft aerodynamic characteristics, course, speed, and altitude
- Instrument lag, accuracy, and human interface (audible alarms, etc.)
- The escape maneuver options.

Many of these characteristics are extremely difficult to model and are of limited use for determining the overall safety benefits of AvSP technologies. For example, object geometry is highly specific and, therefore, is only important if a particular geometry causes a problem with the instruments that detect and measure the object. Simulated aircraft aerodynamics, even when modeled at the best fidelity practical, can differ enough from actual aircraft aerodynamics to significantly reduce the accuracy of the calculated accident probabilities. Further, diagnosing when this occurs is difficult. Escape maneuvers also are highly dependent on the situation and difficult to determine because in actual circumstances a pilot’s actions may differ from what he believes he would do if presented the same situation in a simulation.

By comparing the AvSP technologies to a baseline, we eliminate several possible sources of variance in our model and focus on the primary issue: if the AvSP technology delivers more information that is more accurate and more timely, how does that improve the safety of the aircraft? The analyst needn’t worry about whether the aerodynamic model is absolutely precise or the escape maneuver perfectly mirrors the pilot’s actual actions because both the baseline and the variant will use the same aerodynamics model and the same approach maneuver. Geometry also is not a concern because both the baseline and the variant aircraft will see the same geometry. Ultimately, what matters is exactly what should matter: the differences in instrument characteristics and the differences in how the human operators interact with those instruments in both the baseline and the variant case.

Synthetic Vision: Terrain Avoidance Scenario

Modeling the Probability of Failure

The specific SVS hardware is only processors and displays. Operating the system depends, however, on the several other airborne, ground, and space systems, such as the aircraft autopilot and flight management systems, local area augmentation system (LAAS) ground facilities (LGF), and GPS satellites. The analysis of failure must include the operation of these other systems. Figure 3-1 is a fault tree diagram of the components included in SV for terrain avoidance scenarios. The fault tree shows what is necessary for a completely functional system and indicates that the system fails if any of the systems fail. Failure of certain items will degrade the system without causing it to fail. We can analyze degraded modes by using combinations of the results of individual elements.

Figure 0-1. SV Terrain Avoidance Reliability Components

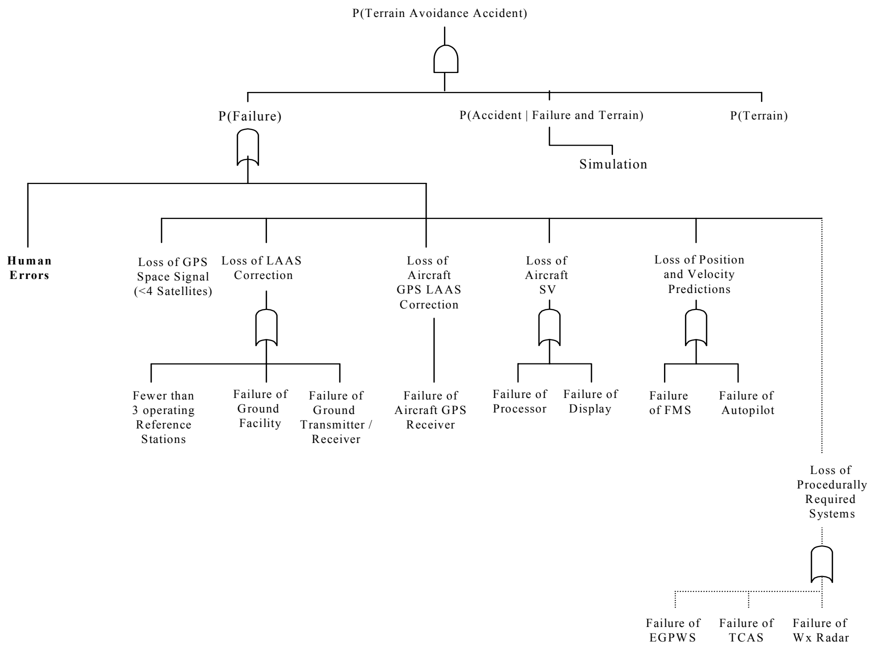

P(Terrain Avoidance Accident)
P(Failure)
P(Accident | Failure and Terrain)
P(Terrain)
Simulation
Human Errors
Loss of GPS Space Signal (<4 Satellites)
Loss of LAAS Correction
Loss of Aircraft GPS LAAS Correction
Loss of Aircraft SV
Loss of Position and Velocity Predictions
Fewer than 3 operating Reference Stations
Failure of Ground Facility
Failure of Ground Transmitter / Receiver
Failure of Aircraft GPS Receiver
Failure of Processor
Failure of Display
Failure of FMS
Failure of Autopilot
Loss of Procedurally Required Systems
Failure of EGPWS
Failure of TCAS
Failure of Wx Radar

Table 3-1 contains the reliability results for the terrain avoidance case, based on a 10-hour mission. The table includes both the probabilities of individual failures and the combined probabilities that relate to total system availability.

Table 3-1. Reliability Results for SV Terrain Avoidance

	Operational	Failed Safe	Failed Unsafe
>=4 GPS Satellites	**0.998988**	**1.01E-03**	
>=3 LAAS reference stations	**1.000000**	**1.34E-09**	
LAAS ground facility	**0.999495**	**1.10E-04**	**3.95E-04**
LAAS transmitter, receiver, antenna	**0.999182**	**8.18E-04**	
GPS receivers	**0.999990**	**2.47E-07**	**1.00E-05**
SVS processor & displays	**0.999999**	**1.23E-06**	**2.25E-08**
FMS processor & radios	**0.9999975**	**2.67E-07**	**2.20E-06**
Autopilot	**0.998901**	**1.08E-03**	**1.50E-05**
Total cumulative probability results	**0.996556**	**3.02E-03**	**4.22E-04**

One of our reference documents[1] discusses three types of synthetic vision applications: safety system, strategic, and tactical. The required probabilities of failure for these applications are on the order of 10^{-5}, 10^{-7}, and 10^{-9}, corresponding to *non-essential* equipment, *essential* equipment, and *critical* equipment, respectively. Applications of SV safety enhancements, such as basic terrain awareness and CFIT prevention (modeled in our scenario), are considered to be in the category of least-demanding requirements. This may seem odd, but the criteria are based on the necessity for flight. Safety enhancement equipment, such as the traffic alert and collision avoidance system (TCAS), enhanced ground proximity warning system (EGPWS), and SV, are *non-essential* for flight. When used for strategic applications, such as flight planning and monitoring in terrain, SV becomes *essential.* When used for tactical applications, such as

[1] *Preliminary System Requirements for Synthetic Vision*, Both, Klein, Koczo, and Lamb, Rockwell Collins Final Report, NASA Contract NCA1-125, Task 11.10.4, December 1998.

"flying the image" and precision approaches, reliable SV operation becomes *critical.* Because many of the economic benefits are based on tactical applications, we expect the SVS ultimately to be designed to meet the highest level of reliability.

The components in the table represent our current understanding of the SVS. We note that the total reliability in the table is well below the "extremely remote failure" level (probability of 10^{-7} to 10^{-9} for failure per flight hour) nominally used by the Federal Aviation Administration (FAA) for critical safety of flight equipment. Reliability can be increased by adding more redundant components within elements. Also, supplemental equipment, such as weather radar, can be used to independently verify the accuracy of SV and essentially eliminate undetected failures. We expect as the SVS is developed for certification, our analysis will show corresponding improvements in reliability.

Reliability also is affected by specific scenario parameters. The reliabilities in the table are based on a 10-hour mission. This is a "standard" time that NASA analysts recommend for avionics equipment. In practice, system certifications generally require more complex performance-based reliability criteria. For example, for the LGF, the FAA specification (FAA-E-2937) states:

> The probability that the LGF broadcasts erroneous data, or that one or more failures exist that affect the smoothed pseudorange corrections from more that one reference receiver for 3 seconds or longer shall not exceed 1×10^{-8} in any 150-second interval.

Similarly for Category 3 landing systems, Appendix 3 of FAA Advisory Circular 120-28D includes the following:

> **6.3.1. Landing System Performance.** All types of low visibility landings systems, including automatic flight control, guidance for manual control, and hybrid, shall be demonstrated to achieve the performance accuracy with the probabilities prescribed in this section. The performance values may vary where justified by the characteristics of the airplane.
>
> The performance criteria and probabilities are as follows:
>
> ◆ Longitudinal touch down earlier than a point on the runway 200 feet. (60m) from the threshold to a probability of 1×10^{-6};
>
> ◆ Longitudinal touch down beyond 2,700 ft.(823m) from threshold to a probability of 1×10^{-6};
>
> ◆ Lateral touch down with the outboard landing gear more than 70 ft. (21.3m) from runway centerline to a probability of 1×10^{-6}.

Detailed performance specifications, such as those above, have yet to be developed for strategic and tactical applications of SV. As analogous requirements are defined for SV, our model can be modified and used to calculate the reliability in specific scenarios for operating time and failure conditions.

Modeling the Conditional Probability of an Accident

Scenario Geometry and Physical Parameters

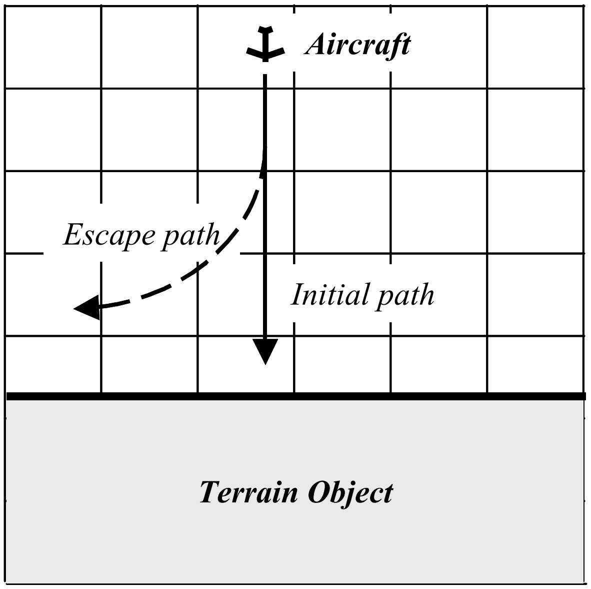
A terrain object is composed of one or more block elements. Ideally, the desired metric—the overall improvement in safety that SVS provides over ATC monitoring—should be independent of the terrain object's size and shape. By comparing the performance of an SV-equipped aircraft to that of a non-SV-equipped aircraft, we ensure that the terrain geometry does not matter. The shape of the object will be the same for both. Therefore, we can choose a relatively simple geometry without losing model fidelity.

We chose to model the terrain object as a semi-infinite face. Thus, an aircraft flying directly toward the object must make a full 90-degree turn to avoid it. A single long, block element can approximate a semi-infinite face.

The aircraft flies directly towards the terrain object at an appropriate speed for final approach. When the flight crew determines that the aircraft is off-course and headed toward a terrain obstruction, the aircraft executes a level turn at speed. When the aircraft completes this turn, the simulation ends.

The geometry for this scenario is simple (Figure 3-2). As a result, running many such scenarios in a Monte Carlo fashion is computationally efficient. The reconfigurable flight simulator (see LMI report NS115S1, *Selection of a Simulation Programming Environment for Air Safety Simulations: The Reconfigurable Flight Simulator*) operations, not the scenario calculations, comprise the bulk of computation time required.

Figure 0-2. Geometry of the SV Terrain Avoidance Scenario



In real life, the pilot's escape maneuver would be highly dependent on geometry, and may require a horizontal component (turn) as well as a vertical component (climb). A turn-climb also may bleed speed, which could place the aircraft closer to its stall speed. Bleeding speed could lead to a secondary source of an accident: the aircraft could stall and fall to earth rather than hit the terrain object. During a discussion with a commercial airline pilot, we learned that a pilot might not execute a turn-climb because of a directive from air traffic control (ATC). Unless the pilot sees that he is in imminent peril, the pilot maintained that his escape maneuver usually would be a level turn.

The physics of a turn-climb maneuver are not excessively more difficult to model than a level turn, but they are not appropriate in this case. We suspect that the pilot would be more likely to consider making a more drastic escape maneuver because of the visual display on the SV equipment than because of directions from ATC only. However, currently, we have no basis for quantifying that likelihood. Therefore, a more conservative assumption is that the pilot would execute a level turn regardless of the equipment that prompts the maneuver.

The level-turn scenario has the following input physical parameters:

- *Envelope distance*: the indicated distance, in feet, between the aircraft and the terrain object when the action sequence starts. In other words, the pilot and ATC do not start corrective action until the aircraft crosses this threshold. We varied this value from 6,000 and 32,000 feet to determine how the probability of an accident varies with envelope distance.

- *Accident or incident distance*: the exact distance, in feet, between the aircraft and the terrain object at which we assume an accident occurs. We set this distance at 500 feet.

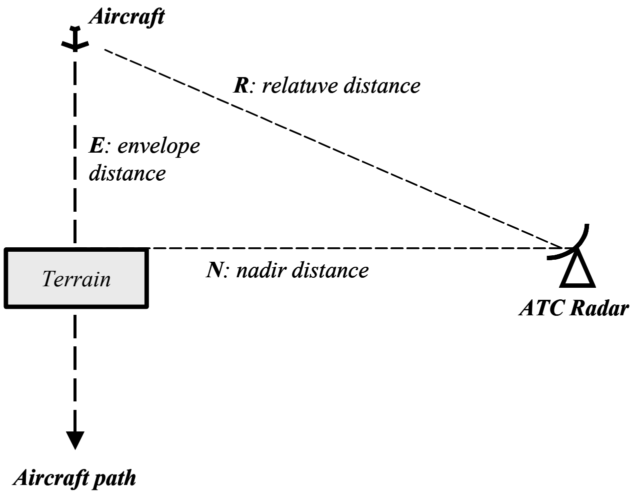
- *Aircraft speed*: the magnitude of the aircraft's velocity in knots. We set the speed at 210 knots for all simulation runs.
- *Steady state turn radius*: the number of degrees per second that the aircraft turns during the escape maneuver. This value is a function of the speed and bank angle of the aircraft. We used three separate turn rates: 1.4°/s, 3.0°/s, and 5.3°/s. These values correspond to a 15-degree bank angle, a 30-degree bank angle, and an estimated maximum safe bank angle for a Boeing 757 at 210 knots.
- *Roll into turn time*: number of seconds for the aircraft to linearly increase its turn rate to the steady state turn radius. We set this value at 2 seconds.

INSTRUMENTATION

The baseline scenario uses ATC radar as the primary terrain detector. The ATC radar has a 5.0-second sweep time; therefore, it measures a new distance between the aircraft and the terrain object once every 5 seconds. The error in this distance measurement is proportional to the relative distance between the location of the ATC radar and the aircraft. This is an approximation of the radar's actual error characteristics, which would include an azimuth error and a range error.

We considered only azimuth error for the aircraft at the envelope distance *E*, according to a fixed nadir distance *N* between the aircraft and the radar as shown in Figure 3-3. The terrain object is located along the nadir line. We placed the ATC at a 50,000-foot nadir distance from the flight path, and assume a 1.2° azimuth resolution for the radar. We estimated that the error varies between 2.1 percent–2.5 percent of the relative distance *R* between the aircraft and the ATC radar, when the aircraft is within 32,500 feet of the terrain object. With a fixed envelope distance, we set the radar's error according to the maximum error in that envelope. For example, when the scenario's envelope distance was 12,000 feet, we set the radar error to 2.1 percent of the range. When the envelope was 32,500 feet, we set the radar error to 2.5 percent of the range.

Figure 0-3. Placement of ATC Radar in the Terrain Avoidance Scenario



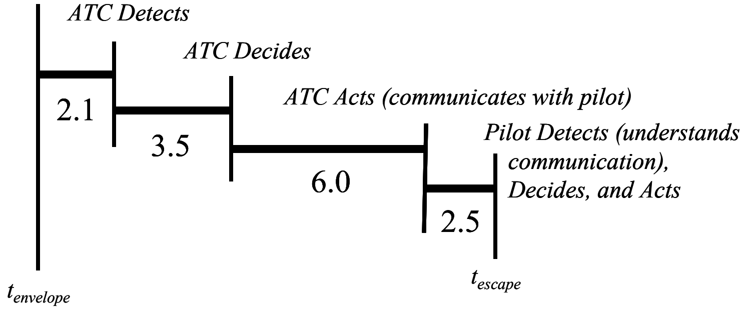
We assume that the SVS is a GPS-based, LAAS-augmented instrument. We further assume that its update rate is near real-time; specifically, we assume that its update rate is much less than the scenario's simulation step interval of 1.0 second. Within the envelope of the scenario, the error for the SVS should be independent of the distance between the aircraft and the terrain object. We therefore specified that the SV-equipped aircraft would know its distance to the terrain object within ±50 feet throughout the simulation. Discussions with researchers from the NASA AvSP SVS Project Office indicate that this is a reasonable value to use.

HUMAN FACTORS AND ACTION SEQUENCE

The action sequence for the baseline case has four basic stages (Figure 0-4). After the aircraft falls inside the envelope distance according to the ATC radar's indication, the ATC must detect that this has happened. The expected value for that first step is 2.1 seconds. After the ATC has detected the condition, we expect that the controller needs another 3.5 seconds to decide on the proper corrective action to take. Once he has done so, he must contact the pilot and instruct him to avoid the terrain. This action has an expected duration of 6.0 seconds. This duration includes the possibility that communications will be blocked, and will, therefore, have to be repeated. Once the controller and the pilot successfully communicate, the pilot is expected to need an additional 2.0 seconds to understand the communication, decide what to do, and act. At that time, the aircraft initiates a level turn escape maneuver.

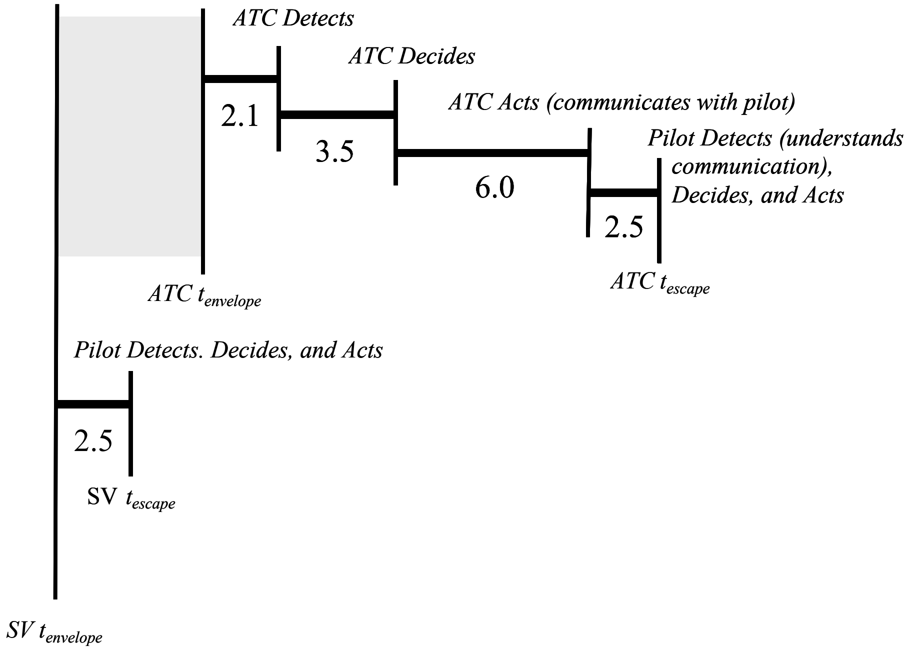
Each of the random variables that determine the controller's and pilot's stochastic action times are geometric random variables. That is, a fixed probability exists that a human actor will complete the current action stage for each simulation step in the sequence.

Figure 0-4. Baseline Action Sequence


ATC Detects
ATC Decides
ATC Acts (communicates with pilot)
Pilot Detects (understands communication), Decides, and Acts
2.1
3.5
6.0
2.5
$t_{envelope}$
t_{escape}

The SV variant of the scenario is based on the assumption that the controller and the pilot both work in parallel to ensure the safety of the aircraft. That means that the controller's action sequence, occurs concurrently with the pilot's action sequence. Now the pilot has two sources prompting him to initiate an escape maneuver: the SV indicator in his cockpit, and communication from the air traffic controller. The SV indicator can prompt the pilot to take action as soon as its indicated distance falls within the envelope distance for the scenario. When this occurs, the pilot is expected to detect that condition, decide what to do, and do it within 2.5 seconds. As soon as the ATC radar also shows that the aircraft has passed within the envelope, the controller also takes steps to correct the problem. Because of the difference in accuracy and update rates between the two detectors, the ATC radar may take as much as 6 seconds longer than the SVS to determine that the aircraft has crossed the threshold. See Figure 3-5.

Figure 0-5. SV Action Sequence


ATC Detects
ATC Decides
ATC Acts (communicates with pilot)
Pilot Detects (understands communication), Decides, and Acts
2.1
3.5
6.0
2.5
ATC $t_{envelope}$
ATC t_{escape}
Pilot Detects. Decides, and Acts
2.5
SV t_{escape}
SV $t_{envelope}$

The pilot's action sequence is much simpler than the controller's sequence. Also, the pilot may start to act as much as 6 seconds sooner. These two human factors characteristics show why synthetic vision, given this set of modeling assumptions, should have a significant safety advantage over ATC monitoring alone.

Metrics

The primary metric for the terrain avoidance scenario is the conditional probability of an accident. The simulation records an accident each time the aircraft flies within 500 feet of the terrain object. The user must determine the accident probability by dividing the total number of accidents in a batch of simulations by the total number of simulations in that batch.

The simulation also records the following summary data:

- *SV envelope time* (if applicable): the time, in simulation steps, when the SV detector determines that the aircraft has come within the envelope distance. Each simulation step takes 1 second.
- *Pilot detection, decision, and action time for SV* (if applicable): time, in simulation steps, when the pilot responds to SV indication and initiates an escape maneuver.
- *ATC envelope time*: the time, in simulation steps, when the air traffic controller's radar indicates that the aircraft has come within the envelope distance.
- *ATC detection time*: the time when the air traffic controller first detects a problem requiring action.
- *ATC decision time*: the time when the controller decides to communicate with the pilot to resolve the problem.
- *ATC–pilot communication time*: the time required for the controller to communicate the problem to the pilot.

- *Pilot detection, decision, and reaction time for ATC*: the time required for the pilot to understand the controller's instructions and initiate an escape maneuver.
- *Minimum measured distance*: the minimum exact distance between the terrain object and the aircraft for a particular simulation.

All of these values enable the user to reconstruct the event sequence for each simulation. Also, the user can derive other interesting metrics for the scenario from the above data:

- Percent of SV simulations in which SV prompts the pilot before ATC does
- Elapsed time for total action sequence.

These metrics are not as important as the total accident probability, but they give the analyst more information about the relative merits of SV.

RESULTS

On the basis of our discussion with the commercial airline pilot, we believe that using three separate turn rates when generating results was prudent. We also believe that considering a range of envelope distances—the starting threshold for the scenario's action sequences was important. We increased the envelope distance because of our assumption that the failure that places the aircraft in a hazardous condition occurs further away or is detected further away from the terrain. When the hazard occurs farther away, the controller and the pilot of the SV-equipped aircraft have more opportunity to correct the problem before an accident occurs.

The scenario had a relatively simple geometry and action sequence. That made it feasible to compute best- and worst-case accident probabilities analytically. We used these numbers to estimate the number of runs necessary to get reasonable results at each envelope distance. We also used the analytic values to check the validity of the model. This comparison made us confident that the model worked as intended.

Table 3-2 is a summary of the 36 batch sets that we ran and their resulting accident probabilities. The accident probabilities shown are based on a failure occurring that leads to the aircraft reaching the envelope distance without detecting a problem. The accident probabilities also have limited meaning when considered as absolute values. We must compare the SV cases with similar ATC-only cases to evaluate the benefit of the SV technology.

Table 3-2. Results Summary

Batch Set	Turn Rate (°/s)	Envelope Distance (feet)	Baseline (ATC-only) or Variant (SV and ATC)	$P_{accident}$
1	**1.4**	**17,500**	**Baseline**	**9.50×10^{-1}**
2	**1.4**	**20,000**	**Baseline**	**5.10×10^{-1}**
3	**1.4**	**22,500**	**Baseline**	**3.10×10^{-1}**
4	**1.4**	**25,000**	**Baseline**	**7.60×10^{-2}**
5	**1.4**	**27,500**	**Baseline**	**4.33×10^{-2}**
6	**1.4**	**30,000**	**Baseline**	**1.28×10^{-2}**
7	**1.4**	**32,500**	**Baseline**	**5.00×10^{-3}**
8	**1.4**	**15,000**	**Variant**	**1.00**
9	**1.4**	**16,250**	**Variant**	**2.58×10^{-1}**
10	**1.4**	**17,500**	**Variant**	**8.42×10^{-2}**

Table 0-2. Results Summary (Continued)

Batch set	Turn Rate (°/s)	Envelope distance (feet)	Baseline (ATC-only) or variant (SV and ATC)	$P_{accident}$
11	**1.4**	**18,750**	**Variant**	**1.27×10^{-2}**
12	**1.4**	**20,000**	**Variant**	**2.90×10^{-3}**
13	**3.0**	**10,000**	**Baseline**	**8.90×10^{-1}**
14	**3.0**	**12,500**	**Baseline**	**5.10×10^{-1}**
15	**3.0**	**15,000**	**Baseline**	**2.45×10^{-1}**
16	**3.0**	**17,500**	**Baseline**	**1.00×10^{-1}**
17	**3.0**	**20,000**	**Baseline**	**3.07×10^{-2}**
18	**3.0**	**22,500**	**Baseline**	**1.19×10^{-2}**
19	**3.0**	**25,000**	**Baseline**	**3.60×10^{-3}**
20	**3.0**	**7,500**	**Variant**	**1.00**
21	**3.0**	**8,750**	**Variant**	**1.80×10^{-1}**
22	**3.0**	**10,000**	**Variant**	**6.33×10^{-2}**
23	**3.0**	**11,250**	**Variant**	**7.33×10^{-3}**
24	**3.0**	**12,500**	**Variant**	**2.01×10^{-3}**
25	**5.3**	**7,500**	**Baseline**	**7.90×10^{-1}**
26	**5.3**	**10,000**	**Baseline**	**4.20×10^{-1}**
27	**5.3**	**12,500**	**Baseline**	**1.90×10^{-1}**
28	**5.3**	**15,000**	**Baseline**	**8.00×10^{-2}**
29	**5.3**	**17,500**	**Baseline**	**2.76×10^{-2}**
30	**5.3**	**20,000**	**Baseline**	**1.20×10^{-2}**
31	**5.3**	**22,500**	**Baseline**	**3.87×10^{-3}**
32	**5.3**	**5,000**	**Variant**	**7.30×10^{-1}**
33	**5.3**	**6,250**	**Variant**	**1.35×10^{-1}**
34	**5.3**	**7,500**	**Variant**	**3.78×10^{-2}**
35	**5.3**	**8,750**	**Variant**	**4.27×10^{-3}**
36	**5.3**	**10,000**	**Variant**	**1.00×10^{-3}**

The data show that, in each case, a combination of SV and ATC monitoring has a significant advantage over ATC monitoring alone. Table 3-3 compares six sets of batch runs in which the variant and baseline cases have a common turn rate and distance envelope. The range of the safety gain is between 11.29 and 420.0 for the six runs. Safety gain is defined as the probability of the baseline-case accident divided by the probability of the variant-case accident. Therefore, a safety gain of 420.0 means that the aircraft is 420 times safer with SV than without SV.

Table 3-3. Safety Gain from Synthetic Vision

Turn Rate (°/s)	Envelope Distance (feet)	ATC only $P_{accident}$	SV and ATC $P_{accident}$	Safety Gain
1.4	**17,500**	**9.50×10^{-1}**	**8.42×10^{-2}**	**11.29**

Table 3-3. Safety Gain from Synthetic Vision (Continued)

Turn Rate (°/s)	Envelope Distance (feet)	ATC only $P_{accident}$	SV and ATC $P_{accident}$	Safety Gain
1.4	**20,000**	**5.10×10^{-1}**	**2.90×10^{-3}**	**175.8**
3.0	**10,000**	**8.90×10^{-1}**	**6.33×10^{-2}**	**14.05**
3.0	**12,500**	**5.10×10^{-1}**	**2.01×10^{-3}**	**253.2**
5.3	**7,500**	**7.90×10^{-1}**	**3.78×10^{-2}**	**20.91**
5.3	**10,000**	**4.20×10^{-1}**	**1.00×10^{-3}**	**420.0**

We did not always run SV batches and ATC-only batches for the same set of envelope distances. At higher envelope distances, the accident probability drops off so severely that we would need an excessive number of simulations to compute it. For a given technology and turn rate, the lower bound on the envelope distance that produces a non-unity accident probability is equal to the turn radius of the aircraft. We determined the upper bound of the envelope distance by estimating the number of simulations required to produce between 10 and 100 accidents. We selected 20,000 runs as the maximum number of runs we would do for any one batch.

The graphs in Figure 0-6, Figure 0-7, and Figure 0-8 show why the range of safety gain is so large. The accident probability does not vary linearly with envelope distance. Rather, the graphs suggest that the relationship has an inflection point at approximately $P_{accident} = 0.5$. Even after this inflection point, the accident probability of the SV and ATC variant drops quickly to near zero as the envelope distance increases. The ATC-only baseline shows a much more gradual decline as envelope distance increases. As a result, the relative safety of the SV and ATC variant becomes larger as envelope distance increases.

The SV and ATC variant is safer than the ATC-only baseline because the expected elapsed time for the human operators to complete their actions is much less for the variant than it is for the baseline. The elapsed time is stochastic; it is in fact a product of a combination of several random variables, as the action sequences in Figure 0-4 and Figure 0-5 show. The elapsed time for the ATC-only case is significantly greater than that for the SV and ATC variant case. From the 1.4°/s turn rate simulations, we estimated the expected value of the ATC-only baseline at 14.05 seconds; we estimated the expected value of the SV and ATC variant at only 1.92 seconds. Clearly, we expect the SV and ATC variant to have a significant time advantage over the ATC-only baseline. The 1.4°/s turn rate simulations showed that when SV is available, the ATC radar will lead to faster corrective action than the SVS only 1.88 percent of the time.

Figure 0-6. Accident Probabilities, 1.4°/s Turn Rate

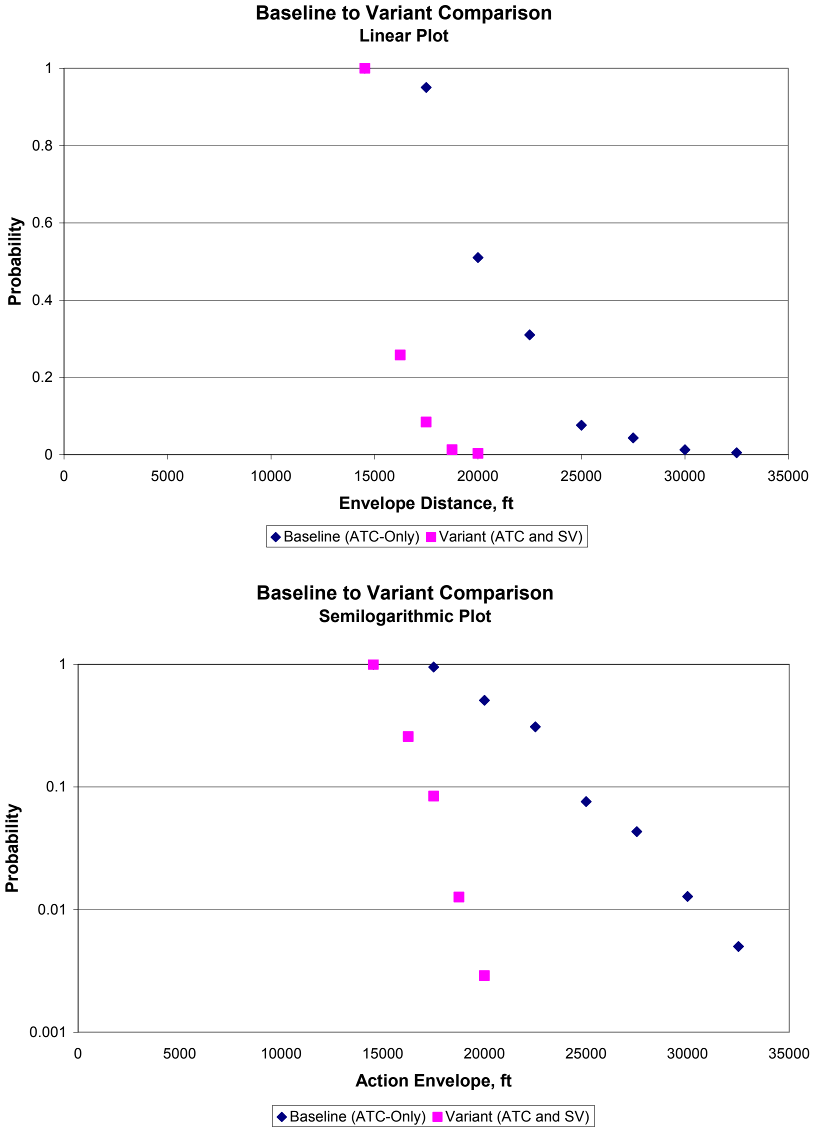


Figure 0-7. Accident Probabilities, 3.0 °/s Turn Rate

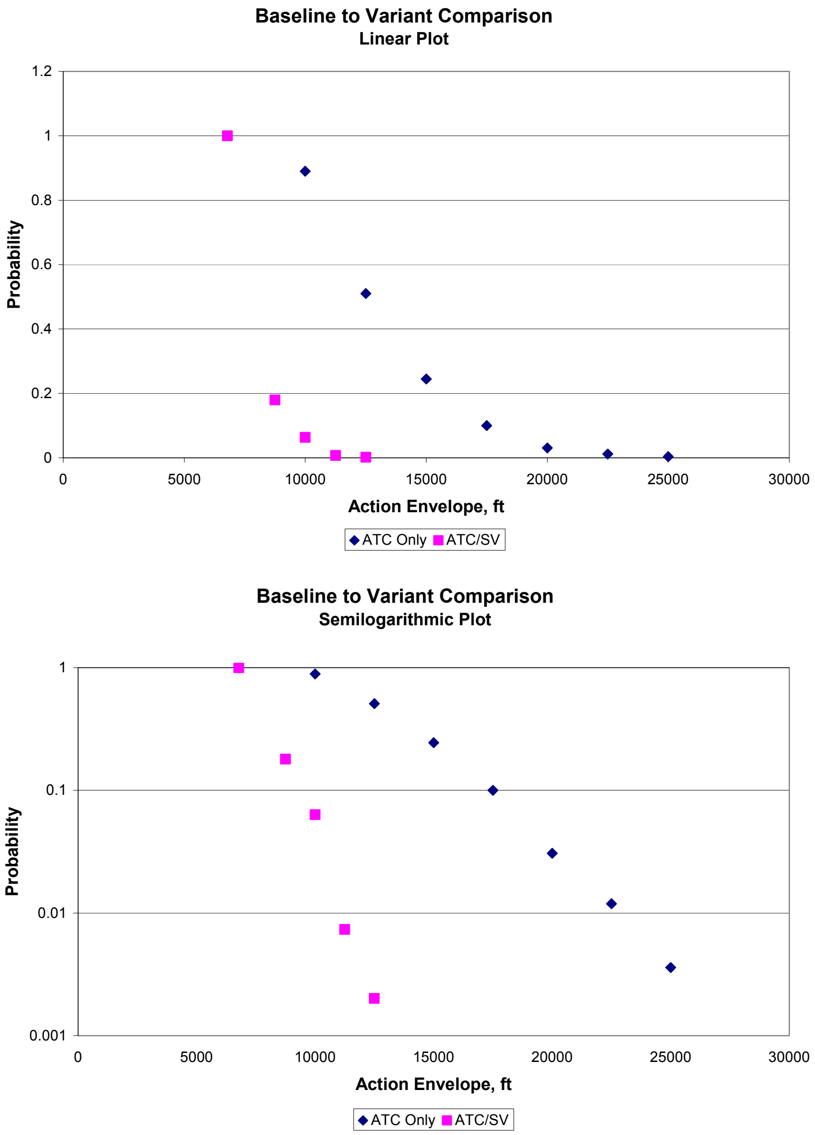
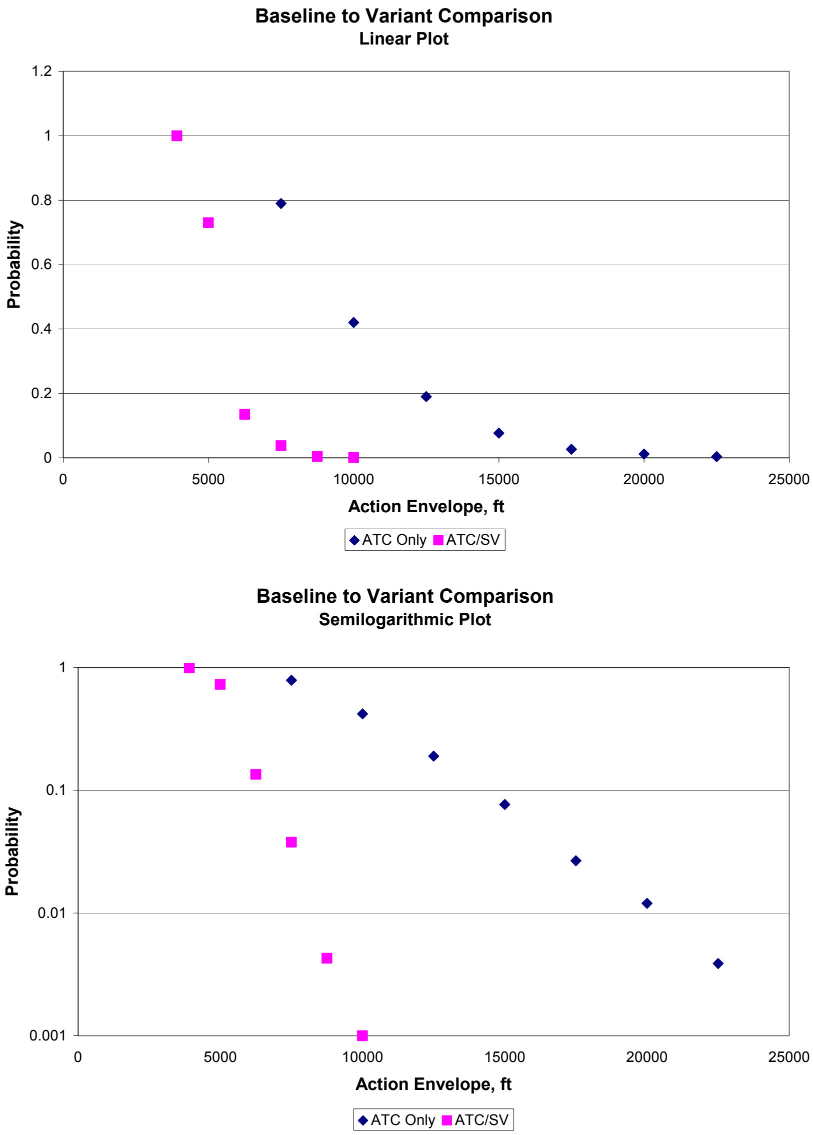


Figure 0-8. Accident Probabilities, 5.3 °/s Turn Rate



Weather Accident Prevention: Turbulence Prediction and Warning Scenario

Modeling the Probability of Failure

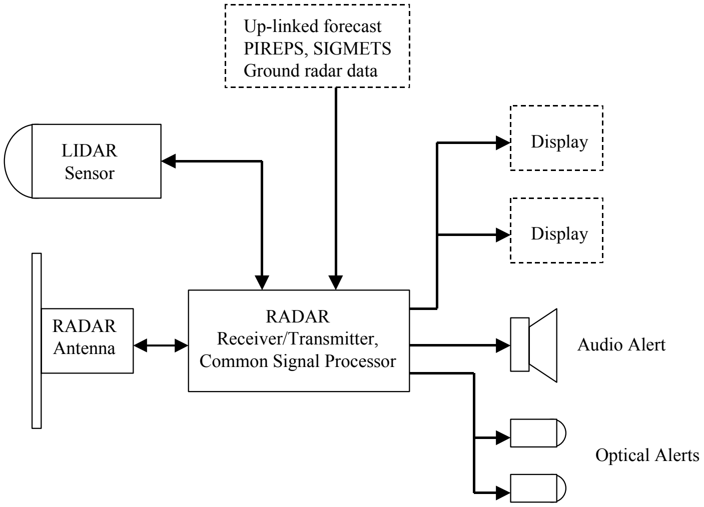
The goal of the Turbulence Prediction and Warning System (TPAWS) program is to "reduce the risk of turbulence-induced injury or death to the traveling public and airline staff by 80 percent in 10 years."[2] The program is focused on the cruise segment of flight. Turbulence of interest, therefore, includes both dry,

[2] Briefing, "Turbulence Detection and Characterization Elements," Rod Bogue, NASA_FAA WxAP Review, Boulder CO, December 1, 2000.

clear air turbulence (CAT) and wet (convective) turbulence associated with storms. Currently, ground-based weather radar can predict and alert for wet turbulence. Pilot reports (PIREPS) are an alternate source of information about wet turbulence and the only source of alerts for CAT. Many segments of flight are not covered by weather radar, and PIREPS are useful for aircraft on well-traveled flight paths that follow the reporting aircraft. The TPAWS technologies include airborne sensors that enable each aircraft to detect both wet turbulence and CAT in sufficient time to prevent injuries.

The hardware suite we are using for modeling is based on that presented by Honeywell, Inc., at the NASA-FAA-Industry workshop on forward-looking (airborne) sensor certification, December 1, 2000. Figure 3-9 depicts the hardware suite. TPAWS technology includes strategic information in the form of PIREPS, Significant Meteorological Information (SIGMETS), and possible Aviation Weather Information (AWIN) Next Generation Weather Radar (NEXRAD) maps.

Figure 0-9. Enhanced Turbulence Detection Components (Honeywell Concept)



Because of the nature of the TPAWS technologies, detection ranges for CAT and wet turbulence are different. Laser radar (lidar) sensors can detect CAT by tracking aerosols at a range of about 5 nautical miles. Microwave radar cannot detect CAT, but can detect wet turbulence by tracking water droplets at a range of about 20-40 nautical miles. This gives us the conditions show in Table 3-4.

Table 0-4. Sensor Capabilities

Radar	Lidar	Dry Turbulence Detection Range (nautical miles)	Wet Turbulence Detection Range (nautical miles)
On	**On**	**5**	**20-40**
Off	**On**	**5**	**5**
On	**Off**	**0**	**20-40**
Off	**Off**	**0**	**0**

HAZARD PROBABILITY (HISTORICAL DATA)

Several hazard probabilities are needed for TPAWS analysis. The basic requirement is the probability of turbulence per flight. The technology performs differently for wet and dry turbulence, so we need the separate probabilities of wet and dry turbulence per flight. In addition, if we assume (based so far on anecdotes and armchair logic) that most injuries occur from unexpected turbulence when there is no ground radar coverage and few or no PIREPS, then we would like to know the probability of (wet and dry) turbulence per flight when traffic density is low or in remote locations (e.g., oceanic flights).

Considerable work has been done in this area. The National Center for Atmospheric Research (NCAR) has collected PIREP data spanning the 10 years from 1992 to the present. They have been analyzing the data statistically for the past 3 years. At this point in our research, we have identified the NCAR data as a starting point for estimating the hazard probability. We have not yet computed a hazard probability, but hope to achieve this as our work progresses.

EQUIPMENT RELIABILITY (MARKOV ANALYSIS)

The quantity and reliability values used for the Markov analysis are shown in Table 3-5.

Table 3-5. TPAWS Component Failure Rates

Component	Quantity	Failure Rate (failures per hour)
Radar receiver/transmitter (R/T), common radar/Lidar data processor	**1**	**1.25×10^{-4}**
Radar antenna	**1**	**1.25×10^{-4}**
Lidar (includes antenna and R/T)	**1**	**1×10^{-3}**
Display	**5***	**6.7×10^{-5}**
Audio alarm	**1**	**6.7×10^{-5}**
Visual alarm	**2**	**6.7×10^{-5}**

*** Two of the five displays must be functioning for full operation**

The failure rates for the displays are based on display mean times between failure (MTBF) of 15,000 hours reported in *Jane's Avionics*. The assumption is that visual and audio alarms have the same reliability as the displays. Failure rates for radar equipment are problematic. Civil weather radar data are, so far, unavailable. Fighter aircraft radars have reported MTBFs ranging from 80 to 300 hours, with the prediction that F-22 radar will have a 2,000-hour MTBF. We assume an MTBF for the combined radar transmitter and receiver of 4000 hours, requiring MTBFs of 8,000 (failure rates of 1.25×10^{-4}) for each component (antenna and receiver/transmitter). The lidar reliability is based on informed speculation. An MTBF of 1000 hours is probably better than any current laser system.

We constructed the Markov analysis to determine state probabilities for cases in which several combinations of sensors and warnings fail. The results are shown in Table 3-6.

Table 3-6. TPAWS State Probabilities

Sensor/Display Condition	Warning Condition	State Probability
Fully operational	**Fully operational**	**9.8626E-01**
Fully operational	**Degraded**	**1.3225E-03**
Fully operational	**Failed**	**2.9673E-10**
Radar only	**Fully operational**	**9.9120E-03**
Radar only	**Degraded**	**1.3291E-05**
Radar only	**Failed**	**2.9822E-12**
Lidar only	**Fully operational**	**1.2336E-03**
Lidar only	**Degraded**	**1.6541E-06**
Lidar only	**Failed**	**3.7114E-13**
Failed (known)	**All cases**	**1.2616E-03**

Degraded warning conditions refer to cases in which some, but not all, of the warning indicators have failed. Failed warning indicators may cause confusion and increase decision time.

The results in Table 3-7 focus on the sensor modes and include the degraded states as operational conditions.

Table 3-7. TPAWS Detection Probabilities

Detection Capability	Probability
Full system	**9.8758E-01**
Radar only	**9.9253E-03**
Lidar only	**1.2352E-03**
Nonfunctional	**1.2616E-03**

Modeling the Conditional Probability of an Accident

For this scenario, we assume that the aircraft is flying into an area in which there is a turbulence cell. We further restrict the scenario to include no PIREPS about this particular cell. Therefore, the aircraft must be able to detect the cell's location if the pilot is to be able to take action to minimize the risk to the aircraft and passengers.

In this scenario, the baseline case is no working turbulence detector. For this case, if the aircraft and turbulence object lie on a collision course, then the aircraft will hit it at full cruising speed and altitude. When it hits, the pilot will immediately reduce the aircraft speed, direct the passengers and crew to buckle in, and request an altitude change from the air traffic controller. The air traffic controller then will grant the change if the traffic situation allows it.

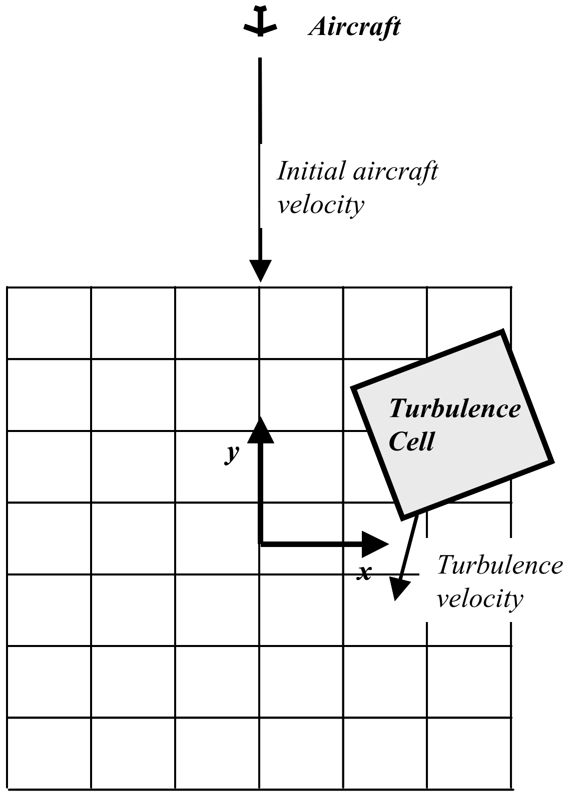
The variant case is a working instrument that detects the turbulence cell at some range. We do not specify the type of turbulence (wet or dry) and, therefore, we can model any type of detector (e.g., weather radar or lidar). Because the WxAP project is developing an X-band radar sensor, that is what we represent in our scenario. However, because the performance of the new sensor is not yet determined, we have run many cases, varying the amount of look-ahead time provided. We used 30 seconds as our initial value because the WxAP project has stated that as the minimum success criteria. Further, the scenario does not address the possibility of false alarms, be they positive or negative. The turbulence cell's intensity will be within the detectable band of the equipment. When the pilot detects a turbulence cell in his path, he reduces the speed of his aircraft and directs the passengers and crew to buckle in. He also requests an altitude change from the ATC, who grants it if the traffic situation allows.

SCENARIO GEOMETRY AND PHYSICAL PARAMETERS

We model a turbulence cell with a single block element in this scenario as well. Unlike the terrain object, however, a turbulence cell can move in the X-Y plane. Also, the turbulence object has an arbitrary orientation with respect to the aircraft's heading. This orientation does not change over time; we assume no rotational component in the cell's velocity.

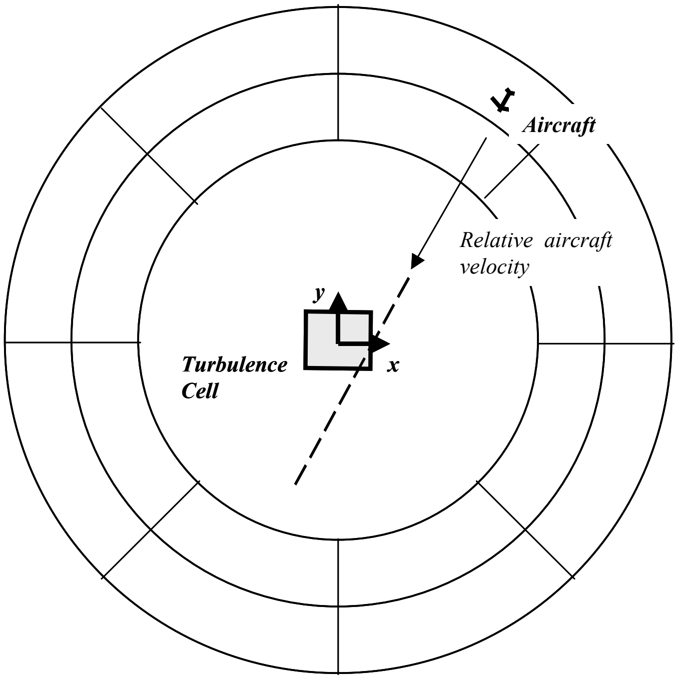
We place the turbulence cell so that its center falls inside an X-Y grid (Figure 3-10). The aircraft flies through the center of this grid at full cruising speed. The turbulence object's velocity (magnitude and heading), orientation and location in the grid are chosen randomly. The aircraft's distance from the grid center at the start of the simulation, its velocity, and its altitude with respect to the terrain object are fixed.

Figure 0-10. Turbulence Scenario Geometry



To increase the scenario's computational efficiency and make the display of a simulation easier for troubleshooting, we transformed the coordinate system above to the equivalent turbulence-cell-centered coordinate system (Figure 0-11). In this coordinate system, the turbulence object's axes are aligned with the global coordinate frame, and the object has a velocity of zero relative to this coordinate frame. The aircraft's velocity and position is computed relative to the turbulence cell. This transformation effectively places the turbulence object at the center of a circular area, and places the aircraft at an arbitrary point in the annular rings shown in Figure 0-11. In this coordinate system, the aircraft either flies by or through the stationary turbulence cell.

Figure 0-11. Transformed Turbulence Scenario Geometry



Although using the turbulence-cell-centered coordinate system simplifies subsequent computations, specifying the physical parameters in the global coordinate system is easier. This scenario has the following input physical parameters:

- *Aircraft distance from grid*: the exact distance, in feet, that the aircraft will fly before crossing into the grid area. This value varies depending on the maximum detection range we choose for the turbulence detector.
- *Grid width and length*: the width and length of the grid in feet. We chose a grid size of 100,000 by 100,000 feet.
- *Turbulence cell length, width, and height*: the dimensions of the turbulence cell in feet. We chose dimensions of 17,500 × 17,500 × 5,000 feet, which is approximately 3 × 3 × 1 mile.
- *Aircraft cruise speed*: the speed in knots that the aircraft flies at the start of the scenario. We chose a ground speed of 480 knots. The airspeed of the aircraft is its speed relative to the turbulence object, because the turbulence object is moving with the winds aloft.
- *Aircraft ideal penetration speed*: the speed, in knots, that minimizes the risk to the aircraft when it flies through a turbulence cell. In the simulation, this speed is 300 knots.
- *Aircraft descent rate*: the rate, in feet per second, at which the aircraft descends to avoid flying into the turbulence, if possible. (We chose to descend rather than ascend on the basis of feedback from our validation and verification committee.) Because the scenario is based on the assumption that the turbulence cell does not

place the aircraft in imminent peril, this rate should be gentle. We selected a 10 feet per second descent rate, which converts to 600 feet per minute.

- *Turbulence cell velocity*: the speed in knots and direction in degrees that the turbulence cell moves. We assume that the turbulence cell does not have a z-component to its velocity; in other words, it neither rises nor falls. The speed is a triangular random variable with a maximum speed of 50 knots, a mode of 15 knots, and a minimum speed of 0 knots. The direction is a uniform random variable with a minimum of 0 degrees and a maximum of 360 degrees.

- *Turbulence cell intensity*: although we do not use this value in the simulation, we generate it using a triangular random variable. The maximum intensity is 1, the mode is 0.3, and the minimum is 0. The resulting intensity is normalized; the analyst can scale it as desired during post-processing.

- *Relative altitude*: The position of the aircraft with respect to the turbulence object, in feet. We specify that the aircraft's altitude coincides with the centerline altitude of the turbulence cell. This means that the aircraft will have to descend 2,500 feet to fly under the cell.

The escape maneuver for this scenario will be to reduce speed, followed by possibly reducing altitude to avoid the turbulence cell. Even if the pilot takes both actions quickly, an encounter remains likely. This is acceptable because contact with turbulence is not as drastic a safety problem as contact with terrain. In reality, the pilot will have several options, and those options become more plentiful as the warning time goes up. The pilot can request to climb, rather than descend. As long as the pilot does not believe an emergency action is necessary (in which case, the aircraft's maximum climb rate and descent rate would determine the appropriate type of altitude change to take), little difference exists between these two actions in this scenario.

The pilot also can change course to fly around the turbulence object, or to skirt its edge if desired. Course changes can be attractive if the change is minor, minimally affecting arrival time, but only if the course change does not conflict with other traffic in the vicinity. By choosing to restrict the aircraft to its original course, we imply that the pilot places a high priority on minimizing flight time. This is a reasonable choice to make if the turbulence cell is mild enough to fly through with a reasonable expectation of safety.

Regardless of the complexity of the escape maneuver, the scenario will provide consistent safety metrics as long as the aircraft performs identical maneuvers in both the baseline and variant cases.

INSTRUMENTATION

This scenario uses a turbulence detector, which provides a distance between the aircraft and the turbulence object. The error on that distance is a uniform random variable of ±2 percent of the distance. The turbulence detector's update rate is 1.0 seconds, which is consistent with the sweep rate of a weather radar. The scenario's simulation step interval is also 1.0 seconds, so the update rate is indistinguishable from a real-time device.

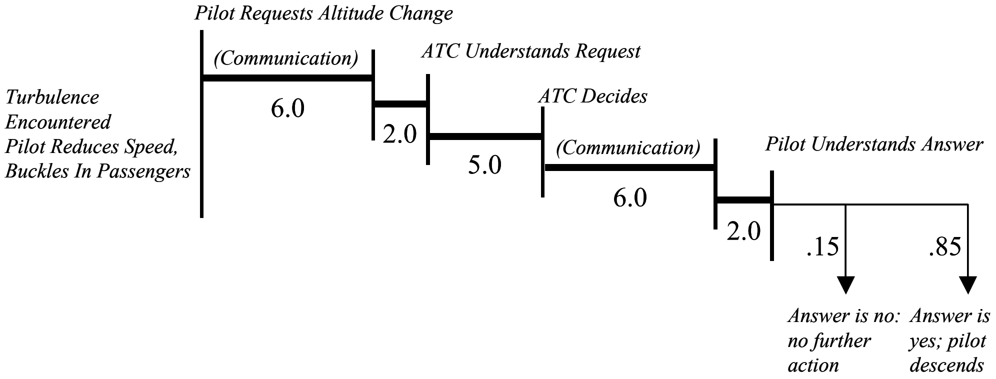
Analysts from the WxAP Project Office informed us that they expect their weather-detection products to give the pilot at least a 30-second warning. We decided to test the following warning times in batch runs: 30, 60, 90, 120, 180, 240, and 300 seconds. We, therefore, adjusted the range of the detector to correspond to the distance the aircraft will fly at 480 knots for the specified warning time. When running a baseline simulation, we set the range of the equipment to zero feet, which effectively removes it from the aircraft.

HUMAN FACTORS AND ACTION SEQUENCE

The action sequence for this scenario is more complicated than the terrain avoidance scenario's action sequence. The pilot must perform several actions, including reduce the speed of the aircraft, request an altitude change, and begin to change altitude. The air traffic controller does not monitor for turbulence cells as he monitors for aircraft that stray too close to terrain. However, he must understand the pilot's request to change the altitude, assess the traffic situation, and grant or deny the request.

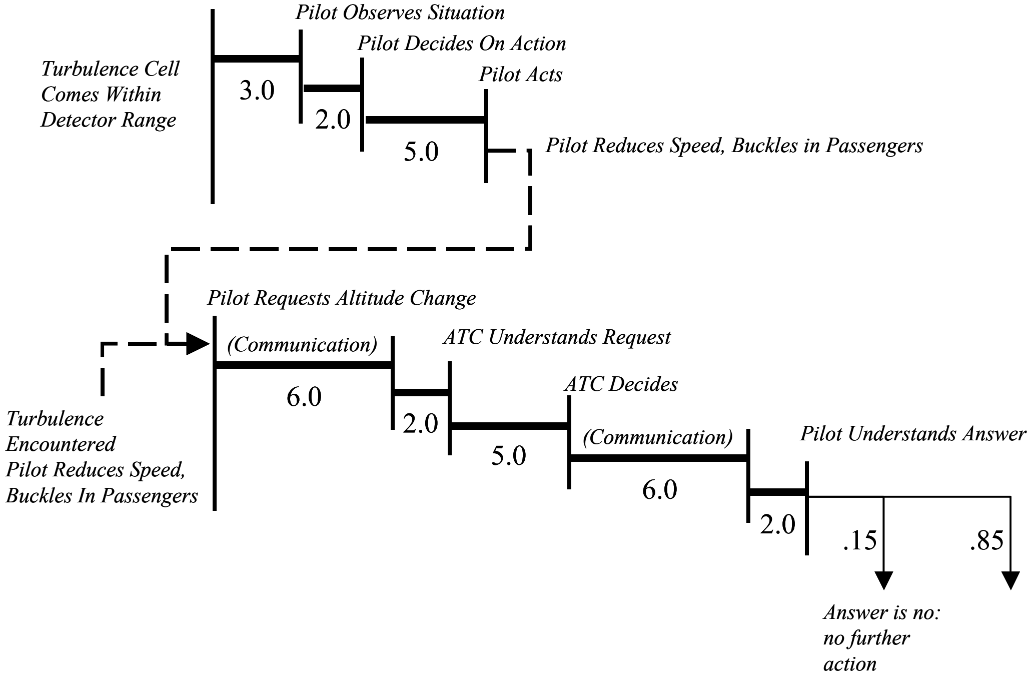
The baseline case includes no detector, so no action will occur unless the aircraft hits turbulence. When this occurs, the pilot immediately begins to reduce the aircraft's speed, turn on the "Fasten Seatbelts" sign, and request a change in altitude (Figure 0-12). This instant reaction is probably optimistic, but it leads to a more conservative comparison between the turbulence-detector-equipped aircraft and the non-equipped aircraft. After taking these immediate actions, the pilot communicates his request to the controller. This task is expected to take 6 seconds. After that communication, the controller must take time to understand the request, which is expected to take 2 seconds, and consider the request, which is expected to take 5 seconds. Once the controller makes a decision, he communicates that decision to the pilot, and the pilot takes time to understand that communication. These tasks are expected to take 6 and 2 seconds, respectively, just as they did in the first communication. Because the pilot is expecting an answer, we assume that he acts on the controller's decision immediately once he understands it. If the decision is no, which has a probability of 0.15, the pilot continues to reduce his speed if necessary, and continues level flight. If the decision is yes, which has a probability of 0.85, he initiates a descent.

Figure 0-12. Action Sequence for the Baseline Turbulence Scenario


Pilot Requests Altitude Change
(Communication)
ATC Understands Request
Turbulence Encountered Pilot Reduces Speed, Buckles In Passengers
6.0
ATC Decides
2.0
5.0
(Communication)
Pilot Understands Answer
6.0
2.0
.15
.85
Answer is no: no further action
Answer is yes; pilot descends

When the aircraft has turbulence-detection equipment, the action sequence becomes more complicated (Figure 0-13). If the pilot encounters the turbulence cell before he observes it on the detector, which is unlikely, the sequence is identical to that of the baseline case. Before the encounter occurs, however, the turbulence detector will show that an encounter is coming. The pilot is expected to take 3 seconds to notice this encounter, 2 seconds to decide on the appropriate course of action, and 5 seconds to implement those actions. When he implements those actions, he requests a change in altitude from the controller, and from then on the sequence is identical to that of the baseline case.

Figure 0-13. Sequence of the Turbulence Scenario Action with Detector



Metrics

The turbulence scenario's safety metrics are less obvious than the terrain scenario's safety metrics. The aircraft probably (and most likely) will be able to fly through the turbulence cell without a mishap of any type. Therefore, computing an accident probability simply by noting that the aircraft has encountered turbulence is incorrect. To arrive at a meaningful measure of the safety benefit of WxAP technology, we must consider several factors in combination:

- *Overall probability of an encounter*: because we placed the turbulence object in a grid and gave it a velocity, the aircraft may not hit the turbulence every time, even when the aircraft takes no actions to avoid an encounter.
- *Altitude escapes*: number of times in a batch run that the aircraft successfully avoids the turbulence cell by flying under it.
- *Full slowdowns*: the number of times in a batch run that the aircraft has the time to decelerate to the ideal penetration air speed.
- *Warning time*: the time interval between the pilot's order to secure the passenger cabin and the aircraft's entry into the turbulence cell.
- *Average speed during encounter*: air speed, in knots.

The analyst must thoughtfully determine how to use these values to assess the safety benefit of WxAP technologies. To assume that safety is proportional to time inside a turbulence cell without considering why the encounter lasts as long as it does is incorrect. For example, if an encounter takes longer than it otherwise would have because the aircraft has slowed to the proper penetration speed, then we can assume that the risk has decreased, even if the encounter lasts longer. If an encounter takes longer than it otherwise would have because a lack of warning has prevented the pilot from steering clear of the cell, then we can presume that the extra time has increased the risk.

The combination of time and speed inside the turbulence cell also is a complex issue. In this scenario, the pilot immediately begins to slow the aircraft from 480 knots to 300 knots when he knows that he will encounter the turbulence. If the pilot manages to slow down to 465 knots at penetration, perhaps the reduction in speed makes the aircraft marginally safer. Also, the aircraft could be less safe: the additional safety afforded by the minor reduction in speed may not make up for the additional risk posed by the increase in time required to pass through the cell.

The LMI safety simulation provides several raw data from which the user can calculate the above metrics. Our simulation does not attempt to translate the metrics into a single safety gain value.

RESULTS

Several things can happen when an aircraft flies the turbulence scenario. Usually, the aircraft will miss the turbulence cell entirely. Without the pilot taking evasive action, the aircraft theoretically will hit the turbulence object in 21 percent of the simulations. We calculated this value by considering the average cross-section length of the cell as measured parallel to the front edge of the grid. If the pilot obtains permission to change his altitude to avoid the turbulence cell, then the probability of hitting the cell diminishes as the warning time increases. The probability does not diminish to zero, however, because the pilot cannot always get permission for an altitude change. In our scenario definition, we specify that the controller does not grant permission 15 percent of the time. When combined with the initial 21 percent chance of encountering the turbulence cell, this yields approximately a 3 percent theoretical probability of an encounter even when sufficient time is available to descend.

Currently, we assume that the WxAP technologies provide a 30-second nominal lead-time before any encounter with turbulence. We received this figure from researchers at the WxAP Project Office. To get a broader picture of the potential benefits of WxAP technologies, we ran seven batches, with nominal lead-times of as much as 300 seconds (5 minutes).

Encounter Probability

Safety is a product of many factors other than the probability of an encounter. However, when considering the potential safety benefit of WxAP technologies, the probability of an encounter is an important factor. Therefore, we discuss it first in Table 3-8.

Table 3-8. Comparison of Encounter Probabilities between Baseline (No WxAP) and Variant (WxAP) Batch Runs

Technology	Nominal Lead-Times (s)						
	30	60	90	120	180	240	300
No WxAP	**0.210**	**0.219**	**0.212**	**0.216**	**0.208**	**0.219**	**0.210**
WxAP	**0.216**	**0.212**	**0.214**	**0.215**	**0.191**	**0.030**	**0.031**

Regardless of its nominal lead-time, each baseline batch run has approximately the same probability of an encounter: 21 percent. This agrees well with the theoretical probability. In the WxAP batch runs, we observed a significant difference once the nominal lead-time reaches 180 seconds. At this time, a combination of slowing down the aircraft and reducing altitude enables the pilot to avoid some of the cells he would otherwise hit. At 240 and 300 seconds, we see that the flight crew has ample time to react to the possibility of an encounter: the probability that they encounter turbulence in these runs is approximately 3 percent, which agrees well with the theoretical minimum encounter probability.

Altitude Escapes and Full Slowdowns

Once a flight crew is aware of an imminent encounter with a turbulence cell, they can plan to avoid the cell entirely if they are willing to accept a course and speed change. In our scenario, we limit the flight crew to one option to avoid the cell: an altitude escape. The aircraft reduces its altitude below the bottom level of the turbulence cell to avoid it entirely. If the flight crew does not have the option of avoiding the cell, the best they can do is slow the aircraft to the ideal turbulence penetration air speed. Taken together, these metrics show the aircraft's ability to respond completely to a potential weather hazard.

Table 3-9 shows two probabilities: 1) the probability that an aircraft avoids the turbulence cell by changing altitude, given that it would otherwise hit the turbulence cell; and 2) the probability that the aircraft can slow down to its ideal penetration air speed, given that it will either hit the cell or avoid it by changing altitude. We show no baseline cases because the aircraft cannot detect turbulence in the baseline case; by definition they never manage to slow down or change altitude before an encounter.

Table 3-9. Altitude Escape and Full Slowdown Probabilities for WxAP Batch Runs

	Nominal Lead-Times (s)						
Avoidance/Mitigation Maneuver	30	60	90	120	180	240	300
Altitude Escape	**0.0**	**0.0**	**0.0**	**0.0**	**0.055**	**0.861**	**0.852**
Full Slowdown	**0.0**	**0.0**	**0.169**	**0.875**	**1.0**	**1.0**	**1.0**

Quite a lot of time is required for the aircraft to get below the turbulence cell from its initial altitude: approximately 250 seconds at a descent rate of 600 feet per minute. Therefore, if the detector gives less than 3 minutes lead-time, we do not expect the aircraft to be able to change its altitude quickly enough, even if the human operators react instantly.

With 3 minutes of lead-time, the aircraft has a small ability to escape an encounter. At first, this may not seem possible: 180 seconds is much less than the 250 seconds required. However, as the aircraft reduces its airspeed in preparation to encounter the cell, it lengthens the time it will take to close the distance. With 4 or more minutes of lead-time, the aircraft will almost certainly escape the encounter each time the controller gives the pilot permission to change altitude. The 85 percent probability of altitude escape matches the 85 percent probability that the controller will allow the pilot to change altitude.

Before the pilot asks for permission to reduce altitude, he begins to reduce the speed of the aircraft. Depending on the initial air speed, the speed reduction could take from 81 to 153 seconds, assuming a deceleration rate of 1.5 knots per second. Accordingly, we see a slight chance of reaching the ideal penetration air speed with a 90-second lead-time. With a 2-minute lead-time, the probability increases to 87.5 percent; beyond 2 minutes, the aircraft almost certainly can fully slow down before the encounter.

Taken together, these numbers show that the WxAP technologies do not allow the pilot much opportunity to complete a full slowdown without at least 90 seconds of lead-time. To be nearly certain that the pilot can complete all of his available actions before an encounter, the WxAP technologies need to be able to provide approximately 4 minutes of lead-time. This does not imply, of course, that the pilot does not have other options for avoiding encountering turbulence, even with only 30 seconds of warning. For example, with 30 seconds of lead-time, he could possibly avoid the encounter with a sharp turn, if that seems necessary. We did not model that possibility because evaluating the ability to avoid a turbulence cell with a sudden turn is not as informative as evaluating the ability to fly below or through turbulence safely.

Warning Time

Warning time is the time from when the pilot first acts to secure the passenger cabin to when the aircraft penetrates the turbulence cell. Ample warning time is critical for ensuring that the passengers and cabin crew have secured themselves in their seats before the turbulence starts to buffet the aircraft. Once again, the baseline case presents no useful data. By definition, the aircraft will have no warning time. The lead-time of the detector is the theoretical maximum warning time at cruise speed. If the pilot notices the turbulence cell as soon as it reaches the detector's maximum range and acts upon it in the same simulation step, then the lead-time and warning time would be similar as we show in Table 3-10.

Table 3-10. Average Warning Time for WxAP Batch Runs

Nominal lead-times	30.0	60.0	90.0	120.0	180.0	240.0	300.0
Warning times	**24.2**	**59.5**	**99.4**	**146.1**	**242.1**	**340.9**	**438.0**

Taken as a group, the batch runs show two conflicting effects that act on the warning time. The delay required for the pilot to notice the problem, decide what to do, and act on that decision is a negative effect. For the 30-second batch run, this delay accounts for the 6 second difference between the lead-time and the warning time. The additional time afforded by slowing down the aircraft is a positive effect. For the 30-second batch run, this positive effect is not enough to make up for the delay caused by human factors. These two factors nearly even out in the 60-second batch run, however. At lead-times greater than 60 seconds, slowing the aircraft adds more warning time than the human-factor delay takes away.

Average Speed during Encounter

The metrics discussed above are a way to measure how safe the aircraft will be as it either penetrates or avoids a turbulence cell. These metrics are straightforward. Metrics that enable the analyst to measure the relative safety of the encounter itself are less clear. For example, one might think that the encounter's average time has a direct relationship to safety: the longer the encounter, the less safe it is. However, this is not true. If it were true, then the pilot would speed up, rather than slow down, to minimize the encounter time.

The aircraft's average speed during the encounter is a better measure of how safe an encounter is. The average speed should be as close as possible to the ideal penetration air speed. Without a detector that gives the pilot time to prepare, the aircraft's actual penetration speed will be its current cruising speed (Table 3-11). The average speed during the encounter will be slightly lower than that because the pilot will slow the aircraft at the first sign of a problem. However, as the batch runs without WxAP technologies show, this speed remains relatively high.

Table 0-11. Average Air Speed During Encounter (In feet per second)

Technology	Nominal Lead-Times						
	30	60	90	120	180	240	300
No WxAP	**787.6**	**787.8**	**788.0**	**788.2**	**789.7**	**789.0**	**789.5**
WxAP	**724.4**	**632.7**	**543.2**	**507.3**	**505.1**	**505.1**	**505.1**

Using WxAP equipment results in a reduction in the average speed. With a 30-second lead-time, the average speed falls 63.2 feet per second. The difference widens as the lead-time goes up until the aircraft reaches the ideal penetration air speed. Judging from the data in Table 3-11, a 2-minute lead-time gives the pilot sufficient warning to enable him to reduce the air speed almost to the ideal penetration speed.

SUMMARY

We do not quantify a single value for the safety benefit of a 30-second lead-time; we can say that the benefits are relatively minor given the constraints of our scenario. On average, the passengers would have 24 seconds of time to secure themselves, and the pilot would have time to reduce his air speed approximately 8.1 percent. He would not have time to reduce altitude appreciably with this lead-time. He may have time to try a more drastic maneuver to avoid the turbulence encounter. To make a turn at full cruising speed, the pilot would need close to the full 30 seconds of lead-time.

As the lead-time increases, the safety benefits become much more significant. Even with the high cruising speed, low deceleration rate, and low descent rate that we've chosen, the aircraft will slow to the ideal penetration speed most of the time with a 2-minute lead-time, and the pilot can routinely avoid the turbulence object by changing altitude with a 4-minute lead-time.

Chapter 4

Remaining Work

We have discussed our progress to-date in modeling the benefits of SV and WxAP. Because this is an interim report, we should consider the results to be preliminary. In addition, we recognize that parts of the SV and WxAP projects have not been addressed by our current scenarios. In this chapter, we discuss the additional scenarios that must be constructed.

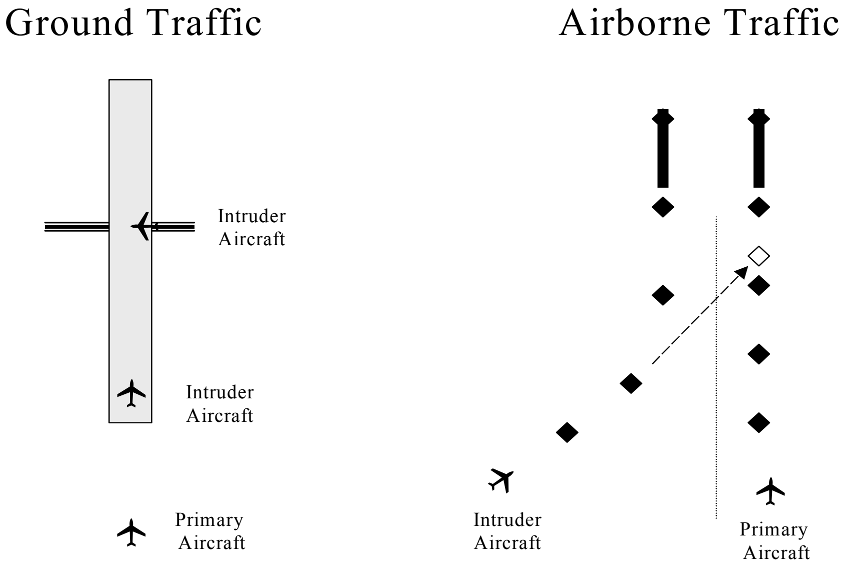
Synthetic Vision: Traffic Avoidance Scenarios

The current work has not addressed either ground traffic or airborne traffic scenarios. In terms of detection, decision, and action, we would model these scenarios much like the existing scenarios. Moreover, the traffic can be considered small pieces of moving terrain.

Figure 4-1 depicts the basic scenarios. The ground traffic scenario will include intruders who cross, or depart on, the arrival runway. The baseline for the ground traffic scenario will be ATC control, with traffic data coming from the Airport Surface Detection Equipment (ASDE) radar, and information transferred to the aircraft by radio telephone (RT). The SV case will include data from the ADS-B or CDTI. The latency and update rates for traffic information will vary depending on the original source of the data and the communication rates of traffic information. Aircraft escape maneuvers will include straight climbs and climbing turns.

For airborne traffic, we will model the "industry standard" scenario in which the primary aircraft is on approach and an intruder ends up heading for the same runway. The baseline will have ATC with traffic data coming from Airport Surveillance Radar (ASR) radar. As above, the SV case will receive traffic data from ADS-B and CDTI. Aircraft escape maneuvers will include climbing turns away from traffic.

Figure 0-1. SV Traffic Avoidance Scenarios



Weather Accident Prevention

Our current weather accident prevention scenario models TPAWS. This, however, covers only one of three elements of the WxAP project. The other two elements are aviation weather information (AWIN) and weather information communications (WINCOMM). Although TPAWS's benefits are mostly gained tactically and are appropriately modeled by simulation, both AWIN and WINCOMM provide strategic benefits. Although the simulation still could work by simply increasing the time horizons from seconds or minutes to hours, we do not believe it is the best way to approach the assessment.

The goal of the AWIN element is to develop technologies and methods, which if implemented, will give pilots sufficiently accurate, timely, and intuitive information during the en-route phase of flight so aircraft accidents attributable to weather situation awareness will be reduced by 25–50 percent.

The goal of the WINCOMM element is to develop advanced communications and information technologies so the flight deck and ground users can disseminate high-quality and timely strategic weather information.

Essentially, the purpose for the two elements is to collect or create high-quality and timely weather information and to develop the infrastructure for delivering that information to pilots. Because the focus is on information, conceiving simulation scenarios to appropriately assess its benefits is difficult.

However, recall that our basic algorithm for estimating safety is

$$P(Accident) = P(Hazard)*P(Accident \mid Failure\ and\ Hazard) \qquad \text{[Eq. 0-1]}$$

where

P(Accident) is the probability of an accident.

P(Hazard) is the total probability of a hazardous condition.

P(Accident | Failure and Hazard) is the conditional probability of an accident given a failure when a hazard exists.

We believe that the benefits of better, more timely information and the communications infrastructure for giving that information can be estimated by the *P(Hazard)* term of our equation. Our idea is that with AWIN and WINCOMM technologies in place, an aircraft's probability of being in a hazardous situation would be reduced. The challenge before us is twofold. First, we must research and determine a baseline probability of an aircraft encountering turbulence or thunderstorms. Second, we must devise a way to measure the reduction in that probability using the new technologies. To start, we could simply use the WxAP goal of achieving a 25–50 percent reduction in aircraft accidents attributable to lack of weather situational awareness. Although using the WxAP goal is easy, as our work progresses, we hope to calculate the benefits more directly rather than simply meeting a stated goal.

Chapter 5

Verification and Validation and NASA Review

Aviation safety is a challenging and sensitive field of work. When human lives are at stake, the attention and gravity are understandable. Similarly, assessing the benefits of technologies that could increase the level of aviation safety attracts scrutiny. As part of our effort, we have presented our methods, assumptions, and results to subject-matter experts for their verification and validation (V&V). We make a distinction between the V&V and NASA's review. The V&V is meant to give us and our task sponsors confidence that our method is sound and that our models represent the human agents, hardware and software systems correctly. To ensure that we represent their projects fairly and accurately, we also have presented our work to the NASA researchers who are developing the technologies. Essentially, the V&V is primarily of our overall approach and baseline scenarios and the NASA reviews are primarily of our variant (with AvSP technology) scenarios.

Verification and Validation

We use the term *verification* to connote a process of checking the software to ensure that it is fully functional and the algorithms in it are providing correct answers mathematically. For our reliability model, if the software is verified, it computes and chains together the failure probabilities and states correctly. For the simulation model, if the software is verified, the algorithms are mathematically correct, random numbers are truly randomly generated, the geometry formulas are correct, and other such mathematics-related processes are implemented and functioning correctly.

We use the term *validation* to connote a process of demonstrating that the software accurately models the specific physical system or process. For our simulation model, if the software is validated, the algorithms, chosen parameters, and the input values used to populate those parameters adequately represent the humans, hardware, and software systems in our scenarios. For the reliability model, if the software is validated, the right components have been identified as comprising the given technology and the physical characteristics of the components, such as input values used for mean time between failure, are accurate.

Our method enables analyzing benefits (reduction of incidents, accidents, encounters) of specific technologies applied in specific scenarios. Our method cannot predict overall NAS-wide accident rates and accordingly, it cannot be validated by historic accident rates. Thus, validation is particularly challenging. Therefore, to assist us in our V&V, we formed a committee comprising subject-matter experts, including a pilot, an air traffic controller, and industry professionals. The roster of the V&V committee is as follows:

- Dr. Andres Zellweger. Dr. Zellweger is working at NASA headquarters for the Aerospace Technology Enterprise and is a dean of graduate programs and research at Embry-Riddle Aeronautical University. He is the former director of Aviation Research at the FAA. Dr. Zellweger reviewed and guided the overall method and soundness of the results.

- Mr. Ralph Dority. Mr. Dority has more than 46 years of experience, including as an air traffic control specialist in both terminal and enroute operations and as an academy instructor in terminal operations of air traffic control. He also is a licensed pilot with an air transport pilot certificate, with type ratings in turbo-jet and single- and multi-engine commercial aircraft and instrument ratings. Mr. Dority reviewed and guided our air traffic controller model and pilot model.

- Mr. Kim Mortensen. Mr. Mortensen is an active pilot for US Airways, for whom he has flown a variety of aircraft types, including the Boeing 737, Boeing 757, and Boeing 767. He reviewed and guided our pilot model and aircraft dynamics.

- Dr. Kevin Corker. Dr. Corker is a professor at San Jose State University and formerly of NASA Ames Research Center. He is a world-renown expert in human factors research with an extensive publication and research history. Dr. Corker reviewed and guided our human factors modeling, including the air traffic controller and pilot models. Dr. Corker also is a paid consultant on our task and, therefore, is not truly an independent arbiter as a V&V committee member. We chose to have him participate because he was paid to review and report on human performance models used for simulations; he has not worked on constructing our models. Nonetheless, we believe that disclosing his relationship to the task is important.

- Dr. Rick Butler. Dr. Butler is a research engineer at NASA Langley Research Center and also the principal author of the core Markov reliability models that we use in our method. As the author, he is uniquely qualified to verify and validate our use of those models.

- Mr. Erkan Yetiskul. Mr. Yetiskul is a software engineer at LMI. He has experience with a range of hardware and software, including C++, Java, UNIX, Oracle, Sybase, and such web-development technologies as JavaScript and XML, across the full system life cycle. Mr. Yetiskul has helped verify our software models and also has assisted us with software quality control and configuration management. Because he is an LMI employee, he may not be considered an independent member of the V&V committee but we have benefited from his software expertise.

We conducted our first V&V review on February 4, 2002. Representing LMI were Shahab Hasan, Bob Hemm, and Scott Houser. Representing the V & V committee were Andres Zellweger, Ralph Dority, Kim Mortensen, and Kevin Corker. Also in attendance was Mel Etheridge of LMI. Mr. Etheridge is not a member of our effort or of the V&V committee; however, he is a former military pilot and has provided ad hoc consultation during the project.

The meeting was very successful. The committee endorsed our overall method and gave us useful feedback about how we have modeled pilots and controllers actions. We reviewed both our general approach and specific parameters. In some cases, we modified the values we had set for items such as reactions times on the basis of the committee's feedback. Probably the most "negative" comment we received was that much of what is important in safety research is what leads to human errors. This was brought up when we were talking about our terrain avoidance scenario in which we postulate that a waypoint entry error (i.e., a failure) has occurred which in turn causes the aircraft to be on a path toward terrain. Although we then model if the pilot and aircraft are able to make an avoidance maneuver by using SV technology, the point was brought up that what is interesting is how or why the waypoint was erroneously entered. We recognize that this is indeed important and interesting but is simply not the focus of our work. An external, detailed human-factors model can compute the probability of an erroneous entry, and our aviation safety simulation would show the conditional probability of an accident. The safety simulation still needs to model human factors, but those human factors are restricted to what happens *after* the separately modeled human error places the aircraft at risk. Other specific comments made during the meeting and our initial responses include the following:

- Pilot reaction times may vary depending on the nature of the indication or alarm. For instance, an audible alarm or flashing red light would elicit faster reactions (and possibly different responses) than would a solid amber light. Currently, our scenarios do not distinguish between types of indications or alarms and thus far, we have nominally handled this by saying that if the pilot hears an alarm or sees a condition out his window, he acts immediately. This is probably adequate for now but should be refined as we proceed, particularly as we delve into SWAP for which we will have to model training benefits and broaden our human factors parameters.

- Pilots may climb, in addition to or instead of turning, when faced with an obstacle (such as in our terrain avoidance scenario). We agree and will be implementing a turn or climb maneuver capability for our aircraft model.

- Pilots almost never exceed 30 degrees of bank in a turn, even in an emergency, unless they have direct indication; i.e., they can see the problem themselves. A pilot would normally respond to a turn command from a controller with a mild turn (15 degrees bank), rather than a maximum performance, or even a 30 degree bank turn. This reaction significantly influences our terrain avoidance scenario because the severity of the turn maneuver directly relates to whether the aircraft is able to avoid the mountain. To handle this limitation, we decided to run three different cases for our scenario runs: 15 degree bank turn, 30 degree bank turn, and maximum performance turn.

- The preferred maneuver for avoiding turbulence, from both the pilot’s and the controller’s perspective, is to descend. We had been modeling the turbulence avoidance as a climb. We have changed to a descent as advised. A descent also makes sense because if the pilot attempted to climb, stalling would be a risk because commercial aircraft typically do not have a great deal of specific excess power (P_s) during high-altitude en route cruise. We do not have to check for this possibility for the descent maneuver.

- The time horizon (proximity to accident) may change reaction times. Currently, we do not vary this. For example, if the expected value for detecting an instrument indication is two seconds, our model will allow that value to vary stochastically but not depending on the time horizon. We may need to insert a conditional branch based on proximity to accident at the time the problem is detected.

- Blocked transmissions between pilots and air traffic control are a big problem. To model this, we have inserted a 20 percent probability of blockage into our simulation.

- Familiarity can lead to complacency, which can increase the likelihood of human failure. On the other hand, unfamiliar situations can as much as double reaction times. Currently, we have not made changes to account for this; however, we will keep this in mind as we begin our SWAP modeling and analysis.

NASA Review

The SV and WxAP technologies that NASA is pursuing are being developed, they are not finished products. Therefore, maintaining contact with the project offices responsible for developing these technologies is prudent to ensure that we are modeling their performance and expected benefits fairly and accurately. Thus far, we have held one meeting with each project office.

Synthetic Vision

We met with personnel from the Synthetic Vision Systems Project Office at NASA Langley Research Center on January 28, 2002. Representing LMI were Shahab Hasan and Bob Hemm. Representing the NASA task sponsors were Mary Reveley of NASA Glenn and Vicki Crisp and Sharon Monica Jones of NASA Langley. Representing the SV project were Dan Baize and Cheryl Allen. We gave a briefing about our overall method; important assumptions; initial results from the SV reliability analysis; and the terrain avoidance scenario, including a software demonstration. No one objected to the overall method but specific comments included the following:

Reliability

- A head-up display (HUD) will have to be retrofitted in "steam-gauge" aircraft because the panel has no room for an SV display.
- SV has degraded, but not failed capability if LAAS reverts to Wide Area Augmentation System (WAAS), to basic GPS.
- The most probable SV installation is HUD with no look-down or HUD and Enhanced Vision System (EVS). The minimum configuration is head-down with a database.
- General Aviation (GA) aircraft would have a single display with no back-up.
- The sensors and databases are basic video channel inputs that could interchangeably go into any video channel destination.
- The reliability values presented in the ADS-B example were questioned as being too low.

We have not yet made changes in our reliability analysis on the basis of these comments but most of the changes or updates necessary will be straightforward. We will try to double-check the ADS-B reliability values (as well as the others that we have computed) to assure ourselves and our task sponsor that they are correct.

Simulation

- The inability of our model to distinguish the safety difference between SV and EGPWS plus ADS-B/TCAS was a major issue. EGPWS has the database information and ADS-B/TCAS will display the traffic information. The SV display has database and display resolution advantages over EGPWS, but the benefit is small (e.g., SV could identify a gap in the mountains that NASA flew during a simulated engine-out departure from Eagle/Vail). SV also promises better overall situational awareness but the benefit is difficult to quantify.

We did not design our simulation to be of the requisite fidelity to resolve the functional difference (and difference in safety benefits) between these systems. Because our baseline is ATC monitoring and pilot control, we are assessing benefits of SV technology relative only to that condition.

Weather Accident Prevention

We met with personnel from the Weather Accident Prevention Project Office at NASA Glenn Research Center on February 19, 2002. Representing LMI were Shahab Hasan and Bob Hemm. Representing the NASA task sponsors were Mary Reveley of NASA Glenn and Vicki Crisp and Sharon Monica Jones of NASA Langley. Representing the WxAP project was Konstantinos (Gus) Martzaklis. Doug Rhone of NASA Glenn and Frank Jones of NASA Langley also attended. We gave a briefing covering our overall method, important assumptions, initial results for the WxAP reliability analysis, and our proposed turbulence detection and avoidance scenario. No one objected to the overall method but specific comments and discussions included the following:

- A discussion took place about the parameters to use for determining a hazard probability in the WxAP analysis. One possibility is to change the probability from 1.0 to 0.5 (the 50 percent WxAP incident-reduction goal). We proposed the idea that the probability of hazard for turbulence would be the probability of encountering turbulence per flight. The NCAR analysis of PIREP data should provide a count of annual turbulent events, and we can count the total flights from the FAA Terminal Area Forecast or Official Airline Guide schedule. The issue was not resolved, but Gus offered to send us an NCAR contact name.

- We discussed the availability of reliability data. A suggestion was that the reliability of the total system should be at least at the level necessary for FAA certification. We need to research the reliability requirements for the different categories of equipment. A comment reportedly was made at the FAA Turbulence Detection Workshop (which none of the meeting attendees had attended) that lidar system developers are aiming for the same reliability as radar.

- We made it clear that we were only analyzing turbulence at cruise conditions. During recent experiments, while sitting on the ground and tilting the lidar on the DC-8 upward, researchers were able to detect convective turbulence. They are considering adding the area from the top-of-descent to 10,000 feet to the research effort, because 40 percent of all weather-related accidents occur in the terminal area. The suggestion was that expanding the analysis to the descent phase might be considered in follow-on studies.

- We discussed and agreed that results of the analysis should include warning time, severity of turbulence, and duration of exposure. Given this data, calculating the number of injuries or severity of injuries may be possible. We currently have no plans to calculate that kind of metric. We had only been considering calculating warning time and duration of exposure, and the duration of exposure is based on our somewhat arbitrary description of the turbulence cell. On the basis of this discussion, we have developed a simple turbulence-cell-strength distribution. Having the probabilities of exposure, length of exposure, and turbulence strength come from external data, such as the NCAR PIREP analysis, and letting the simulation focus on the warning time and avoidance maneuver may make sense. We will be giving this matter more thought as our work progresses.

- There was some discussion of modeling additional aircraft, both for turbulence response and for flying environments. Currently, we do not plan to consider additional aircraft or cruise conditions; however, our simulation model could certainly accommodate that type of analysis.

Appendix
Abbreviations

ADS-B	Automatic Dependent Surveillance—Broadcast
ASDE	Airport Surface Detection Equipment
ASR	Airport Surveillance Radar
ATC	Air Traffic Controller
AvSP	Aviation Safety Program
AWIN	Aviation Weather Information
CAT	Clear Air Turbulence
CDTI	Cockpit Display Of Traffic Information
CFIT	Controlled Flight Into Terrain
CNS	Communication, Navigation And Surveillance
EGPWS	Enhanced Ground Proximity Warning System
EVS	Enhanced Vision System
FAA	Federal Aviation Administration
FMS	Flight Management System
GA	General Aviation
GPS	Global Positioning System
HUD	Head-Up Display
LAAS	Local Area Augmentation System
LGF	LAAS Ground Facilities
MTBF	Mean Times Between Failure
NAS	National Airspace System
NASA	National Aeronautics And Space Administration
NCAR	National Center For Atmospheric Research
NEXRAD	Next Generation Weather Radar
PIREP	Pilot Report
RI	Runway Incursion
RT	Radio Telephone
SIGMETS	Significant Meteorological Information
SV	Synthetic Vision
SVS	Synthetic Vision System
SWAP	System-Wide Accident Prevention
TCAS	Traffic Alert And Collision Avoidance System

TPAWS	Turbulence Prediction And Warning System
V&V	Verification And Validation
VFR	Visual Flight Rules
WAAS	Wide-Area Augmentation System
WINCOMM	Weather Information Communications
WxAP	Weather Accident Prevention